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Sources and Transportation of Bulk, Low-Cost Lunar Simulant Materials

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December 2013

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The many companies that provided samples and information were very important to the success of this effort and noted throughout this Technical Memorandum. See the appendix for a listing. Hannah Wright took the photographs of volcanic cinder cone materials as the rock from McCoy, Colorado.

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LIST OF ACRONYMS AND SYMBOLS

BNSF	Burlington Northern Santa Fe
BSE	backscattered electron
CaF ₂	calcium fluoride
CBC	collapsible bulk container
CFR	Code of Federal Regulations
CO ₂	carbon dioxide
Fe	iron
GSFC	Goddard Space Flight Center
H ₂ O	water
HSC	Hazard Communication Standard
IARC	International Agency for Research on Cancer
IBC	intermediate bulk container
JSC	Johnson Space Center
K	potassium
KSC	Kennedy Space Center
MSDS	Material Safety Data Sheet
MSFC	Marshall Space Flight Center
NAVDAT	North American Volcanic and Intrusive Rock Database
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology

LIST OF ACRONYMS AND SYMBOLS (Continued)

NS	Norfolk Southern
OSHA	Occupational Safety and Health Association
OTM	OSHA Technical Manual
SFVF	San Francisco Volcanic Field
Si	silicone
SiO ₂	silicone dioxide
TM	Technical Memorandum
UP	Union Pacific
US	United States
USGS	United States Geological Survey
XRD	x-ray diffraction

TECHNICAL MEMORANDUM

SOURCES AND TRANSPORTATION OF BULK, LOW-COST LUNAR SIMULANT MATERIALS

1. INTRODUCTION

For any specific procurement of simulant, the avenue chosen will be driven by cost, specific performance parameters of interest, personal knowledge, and personal preference. For users needing large quantities of material to simulate the lunar surface, and able to relax functional requirements sufficiently, there are several very different avenues to obtain low-cost simulants. This is illustrated by the contrast between GRC-1¹ versus GSC-1² and BP-1.^{3,4} GRC-1 is a mechanical mixture of sand and clay; it is designed to emulate a limited range of mechanical properties without consideration of composition or other mechanical properties. In contrast, GSC-1 and BP-1 are waste materials created in the process of crushing basaltic rock.

This Technical Memorandum (TM) summarizes considerations and information gained in the spring of 2013, procuring material to build an outdoor 30 m × 30 m test area at Marshall Space Flight Center (MSFC) called the Lunar Surface Testbed. The testbed was created to test autonomous, hazard avoidance by a rocket-powered lander. For this work, the spectral properties of the simulant were paramount. It was also desired that the testbed ‘look lunar’ and be useful for other types of tests. The design required a minimum of 200 tons of simulant material.

2. ASSUMPTIONS

Readers of this TM are assumed to be NASA employees or contractors. It is assumed that the low-cost simulant material will be brought onto a NASA Center. Unless otherwise noted in the TM, values such as costs are to be understood as being specific to the spring and summer of 2013. The units in this TM mix metric and English. As commerce in the United States is generally done in the latter, retaining English units for values such as weight and distance facilitates use of the contained data.

It should be noted that bringing large quantities of simulant material onto a NASA facility will involve personnel in the base's Facilities, Environmental, Health, Procurement, and Transportation offices. It is recommended these offices be involved in the planning phases of any such effort. Readers are also reminded that access onto NASA property by truckers or heavy equipment operators must also be addressed. A Material Safety Data Sheet (MSDS) may also be needed for the specific material purchased or for a close equivalent. Not all materials have an MSDS. Regulations only require an MSDS for materials meeting certain characteristics, which many geologic materials do not satisfy. Thus, a generic MSDS for scoria may have to be substituted for an MSDS for a specific scoria.

Throughout this TM, specific company and contact information is provided. This is not to be construed as endorsement, but is provided to assist future workers.

3. TRANSPORTATION

Cost includes the original purchase price and the transportation of the material from the provider to the user. Very commonly, the cost of transportation is much greater than the purchase price. For example, the construction of the MSFC Lunar Surface Testbed was initially built using 200 tons of simulant material, which cost \$1,400. The cost to transport it from Flagstaff, Arizona, to MSFC was approximately \$40,000. Therefore, attention to shipping is very important.

The NASA Center Transportation Officers are experts at shipping a vast range of products and materials to their facility. They can arrange the actual shipping. Procurement policy may favor a single contact, i.e., the rock producer provides transportation or the shipper purchases the rock. But most producers of rock materials generally do not arrange shipping and most shippers do not arrange the purchase of rock.

Transportation in multi-ton lots is most economically done by either truck or by rail. To obtain cost estimates of transportation, at a minimum, one has to know the origination and delivery points, the weight of the material, and its approximate bulk density. MSDS and particle size characteristics will probably also be required. For the Federal government, trucking contracts are organized by GSA. A pool of shippers exists who bid on individual jobs, which makes the price competitive.

The options of transporting material from the source to the NASA facility are shown in figure 1.

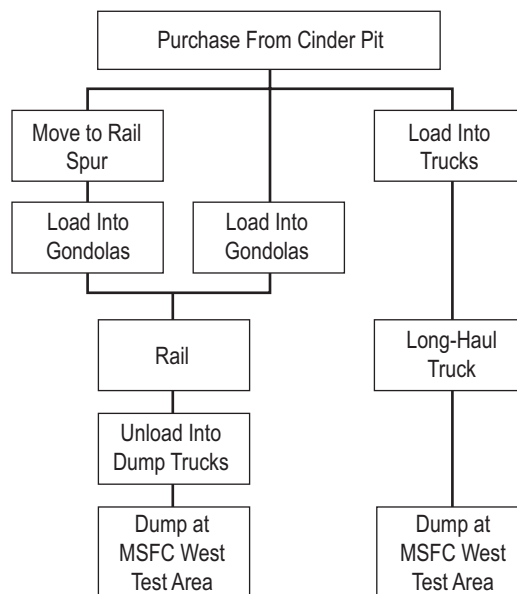


Figure 1. Generic options to transport simulant from source to NASA facility.

3.1 Trucking

As of the spring of 2013, long-haul trucks in the United States (US) can move between 18 and 25 tons per load. There are three trailer configurations that are relevant for this purpose—flat-bed, end dump, and belly dump. Belly dump trailers are also termed hopper or bottom dump trailers. Haulage by flatbed is easily obtained and generally the trucking cost is the cheapest option on a ton/mile basis. However, if the material must be containerized, that is an additional cost.

For containerization, there are two subelements—the cost of the containers and the cost of loading at the quarry. There are several possible containers for shipping. The one most common, and recognized by most quarry operations, is the use of super sacks.

For the movement of bulk, low-cost simulant, there are two relevant types of super sacks: (1) those requiring pallets to be moved by forklift and (2) those having lifts built into the sack (shown in figs. 2 and 3). In quarry operations, loading super sacks is considered a relatively slow process. This is because front-end loaders used in quarries typically have much greater capacity than the super sack, as seen in figure 2, and there is more labor involved in moving the material and the sacks around. Also, special frames are needed to hold the sack open while loading. Therefore, material to be shipped in super sacks will cost considerably more at the quarry mouth than material not in super sacks.



Figure 2. Loading of super sacks at the Miller Mining facility northeast of Flagstaff, AZ (image from Zybek Advanced Products; used with permission).



Figure 3. Load of super sacks on a flatbed trailer (image from Zybek Advanced Products; used with permission).

Although quarries are not familiar with this, the material can also be loaded into and moved in intermediate bulk containers (IBCs) (see figs. 4 and 5), collapsible bulk containers (CBCs), or plastic industrial totes. IBCs are normally used to move liquids; however, the top of the plastic container can be cut loose using a 'sawzall' type of tool. The opened IBCs are easily strong enough to hold bulk simulant material; sand and small gravel-sized material can be loaded by a scoop loader, and they can easily be moved about by a forklift. Both IBCs and CBCs can be bought used at substantial savings compared to new. Unless purchased new, it is important to know what they were previously used for or to have them washed clean.



Figure 4. IBCs being moved by forklift. Photograph taken by author at the Stillwater Mine, Nye, MT; used with permission of mining company.



Figure 5. IBCs showing top of the plastic container removed and then loaded with rock. This was done in support of the NASA/USGS simulant development effort. The rocks were loaded by hand, not by machine. Photograph taken by the author at the Stillwater Mine, Nye, MT; used with permission of the mining company.

When choosing between a super sack, IBCs, CBCs, industrial totes, or other containers, the following should be considered: purchase and transportation cost to the quarry, loading at the quarry, loading onto the truck, unloading at the Center, and emptying procedure. The storage environment will also need to be considered unless the contents are used immediately.

The alternative to flatbed trailers is to use what are called ‘belly dump’ trailers (fig. 6) and ‘end dump’ trailers (fig. 7) . The total weight capacity of each trailer and the particle size limits that can be handled vary significantly.



Figure 6. Belly dump trailer unloading volcanic cinder for the MSFC Lunar Surface Testbed.



Figure 7. Belly dump trailer unloading volcanic ash for the MSFC Lunar Surface Testbed.

Elements in the cost for transportation by truck include the following:

- How far is the material to be shipped.
- Are there any loads the driver can carry on the return trip.
- How soon does the material have to be delivered.
- If there are multiple loads, do they all have to be delivered in a short period of time.
- The cost of fuel.

There is a seasonal aspect to the cost also, especially for end dump operators. Many end dump units are used to supply rock to landscaping operations, which are busiest in the spring and summer.

Estimates received for shipping 200 tons by truck using end dump trailers during the spring of 2013 are shown in table 1.

Table 1. Truck shipping estimate for a 200-ton load.

Distance	\$/Ton	\$/Mile/Ton
1,100	117	0.106
550	92	0.167
1,050	170	0.162
1,050	200	0.19
1,541	214.5	0.139

On July 18, 2013, trucking quotes were requested for a single load of material originating in Flagstaff, AZ, and delivered to MSFC. The quote for an end dump truck was \$5,437.50 and a belly dump truck was \$4,937.50.

3.2 Railroads

Shipping by rail is substantially cheaper per ton/mile than by truck if enough tonnage is moved far enough and sufficient time is available. Moving 200 tons to MSFC by rail from Flagstaff, AZ, is definitely more economical than by truck. By rail, low-cost simulant materials can use aggregate or mill gondolas, which are open top cars designed for this service. Each car can move approximately 100 tons of rock. Gondolas are loaded and unloaded from above. The unloading is done by positioning a backhoe on top of the car and scooping material into an adjacent dump truck. If really large quantities are moved on a continuing basis, bottom dump hoppers or even rotating dump cars can be used, but these require special structures at the unloading location.

Rail transport over several hundred miles will be done by one or more class 1 railroads, such as Burlington Northern Santa Fe (BNSF), Union Pacific (UP), or Norfolk Southern (NS). They will charge based on the type and number of cars and who supplies them, the distance, cost of fuel, the type of material, and the required schedule. The following gives an example quote:

- Leg 1: \$11,210 from Flagstaff to Memphis
 - BNSF rule 11 rate to Memphis is \$4,980/car + mileage-based surcharge of \$0.41/mile (April) \times ~1,525 miles = \$625/car ($\$4,980 + \$625 = \$5,605 \times 2 = \$11,210$).
- Leg 2: \$4,390 from Memphis to Huntsville
 - The NS rate on crushed stone 1,421,990 or volcanic scoria 1,491,410 in railroad supplied cars:
 - Covered hopper/gondola: \$2,195 per car \times 2 cars = \$4,390.
 - Open top, bottom dump: \$1,996 per car \times 2 cars = \$3,992.

The cost per ton/mile is \$0.051.

However, two additional cost elements must be included in this—loading and unloading. Loading and unloading each have two elements that will affect cost. First, use of sidings or spurs is required. Unless the source quarry and the receiving Center have rail facilities they control, there is likely to be a cost associated with use of someone else’s facilities. Second, the operators loading or unloading must be permitted to work on and around railcars. The loading can be done with front-end loaders, conveyors, or other techniques. The unloading of aggregate gondolas is done by placing a backhoe on top of the gondola. The backhoe then moves the material into adjacent dump trucks for transport to the final location. For the unloading at MSFC, estimates were obtained in 2013 of between \$8,000 and \$10,000 for a total of two railcars.

3.3 Comparison of Rail Versus Truck From Flagstaff to Marshall Space Flight Center

It used to be very common for quarries and pits to have rail connection; that is much less common as of this writing. If it is available, it can be a major cost savings. Otherwise, the material must be trucked from the pit to a railhead. There it will be dumped on the ground and loaded into railcars. Finding a siding or spur where the material can be loaded is a substantial problem and there are no sources that provide specific possibilities in a given location. It has been necessary to study imagery of a railroad track in an area as seen by Google and then calling local individuals to get leads to the owners of the siding. Then, it is necessary to find a local contractor willing to do the loading of the rail cars.

Delivery by truck is likely to be quicker than by rail. There are fewer parties involved, and many quarries, especially the smaller ones, only have direct access via truck.

4. GEOLOGY

For a user of simulants, the parameters most commonly of interest are particle size distribution and composition. Grinding rock to a specific size is extremely energy intensive and requires special skills and equipment. Rock that must be ground to meet a particle size distribution specification will no longer be a low-cost material. Therefore, a low-cost simulant must be selected from candidates produced for other reasons or are byproducts. The range of candidates is further constrained by a desire to replicate characteristics of the Moon related to the composition of the particles.

The lunar surface is approximately ‘basaltic’ in composition, meaning it is dominated by the minerals plagioclase, pyroxenes, and olivine in varying abundances. Due to various processes, including volcanism and hypervelocity impacts, a varying percentage of the minerals has been converted to a vesicular glass. The lunar regolith is generally a grey color, contains no oxidized or hydrated iron, and is dominated by very small particles. For detailed information on the regolith, see the *Lunar Sourcebook*.⁵

Assuming that composition is relevant, there are several terrestrial types of rock generally considered suitable for low-cost lunar simulants. All fall within a limited range of chemical composition when expressed as weight percent oxides. To a geologist, the obvious differences between the types are the size of the crystals formed by the minerals and the abundance of glass. Differing combinations of composition and crystal size have specific technical names.⁶ The nonlunar specialist is warned that the lunar geology community has never consistently adopted the International Union of Geological Sciences naming standards. Therefore, that literature must be read with some care with regard to rock names, especially when comparing to the technical descriptions of terrestrial rocks.

When the crystals in the rock are large enough to be readily apparent and plagioclase is the dominant, but not the only significant mineral, the rock will generally be a gabbro. If the crystals are just barely visible to the eye, it may be termed a diabase. Diabase is a term that is no longer used by geologists, but it is present in the older literature, it is used informally, and it is used by some quarry operations. Gabbros and diabases are classed as intrusive rocks, implying the liquid rock did not reach the surface of the Earth. If the crystals are microscopic, the rock is a basalt. Basalts may or may not contain glass. Basalts are classed as extrusive rocks, implying the liquid rock did reach the surface of the Earth. Commercially, gabbro, diabase, and basalt can also be called trap rock. This is especially common with the metabasalts, defined below. For more information on relevant rock naming conventions, see section 1 of Rickman et al.⁷

If the basalt has abundant bubbles—termed vesicles—that are visible to the unaided eye, the rock is called scoria. The vesicles are caused by the gentle exsolution of compounds, such as water (H₂O) and carbon dioxide (CO₂) from the liquid rock before the glass could solidify. If the

exsolution process is more rapid, the escaping gases can blow the magma out the throat of the volcano, much like a shaken container of cola expels the liquid. The liquid rock cools as it travels through the air, forming particles ranging in size from large blocks to micron-sized particles. The larger particles fall closer to the vent and form a cinder cone. The expelled particles are very high in glass and are highly vesicular. Those particles smaller than 2 mm are termed volcanic ash. Material between 2 and 64 mm are lapilli or cinders. Still larger particles are volcanic bombs (fig. 8).



Figure 8. Volcanic bomb from McCoy, CO. The highly vesicular nature of the material is apparent. The original dark-gray material lightens as it weathers, which is easily seen along the left side of the rock; sample provided by Andres Aslan (millimeter scale).

If near surface water is involved in the eruption, the iron (Fe^{++}) in the molten rock can become oxidized to Fe^{+++} . As a result, the particles become distinctly red. The gases involved in the eruption can also deposit minerals such as gypsum. Such minerals are not present or are extremely rare on the Moon and they are also easily seen, even in small concentrations.

The age of a cinder cone is important. In arid climates like the American Southwest, a material called caliche forms as part of the weathering process (fig. 9). All other things equal, the older the material, the more caliche will have formed. Caliche is a white material and nonlunar in composition.

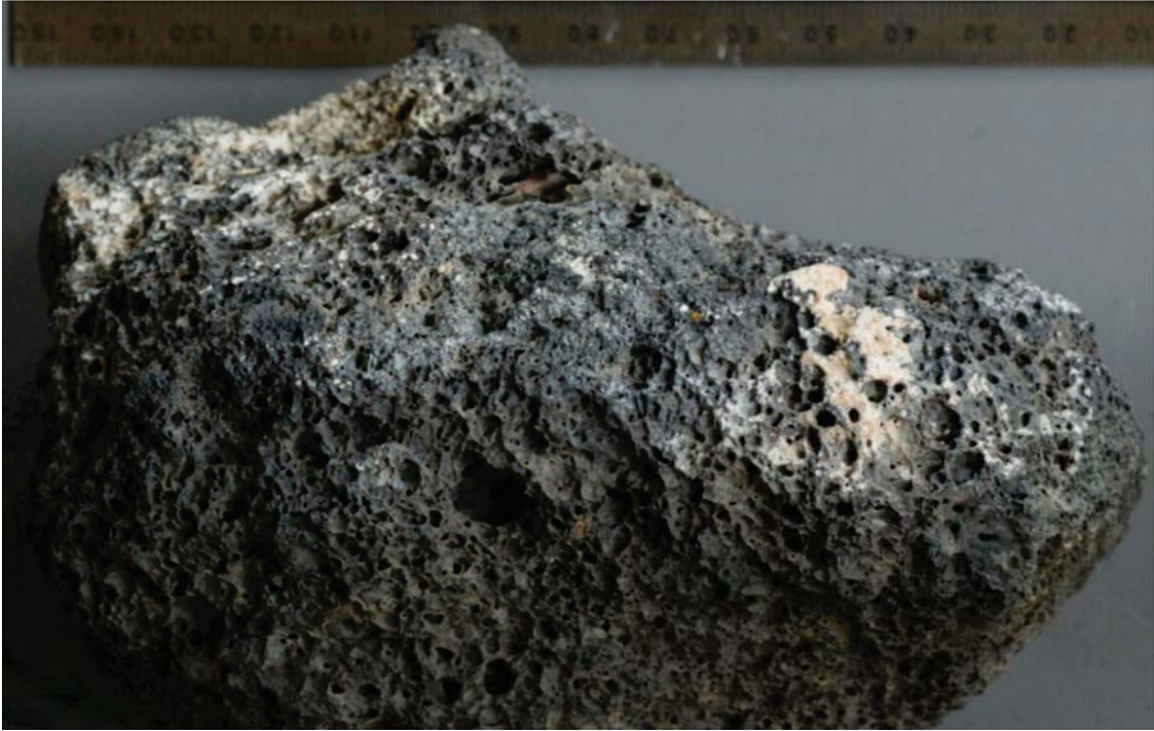


Figure 9. Probable caliche deposit (white) on a volcanic bomb from McCoy, CO; sample provided by Andres Aslan (millimeter scale).

Adding the term ‘meta-’ as a prefix to the rock name means that, after its original formation, the rock has been metamorphosed. This means it has been subjected to enough heat and pressure to noticeably change the original rock. Glass, if originally present, will be converted to minerals, existing crystals may grow or disappear, and new minerals will appear. The new minerals of metamorphic origin, such as serpentine, commonly grow at the expense of any original pyroxenes and olivine. The metamorphic minerals commonly are green, thus the meta-basalts and meta-gabbros tend to have a green cast.

5. PRODUCERS

In the United States there are producers for each of the above types of rocks. By far, most of the production is for use as aggregate and road metal. If the source material is a solid rock, the producing facility is termed a quarry. If the rock is being extracted for reasons other than for aggregate or road metal, the producing facility will usually be called a mine. The mine or quarry operator will blast the stone free from the Earth; it is then crushed.

Postcrushing processes differ in mines and quarries. In mines the rock will be further ground, normally to particle sizes substantially smaller than 1 mm. Then one or more valuable constituents will be extracted using chemical and mechanical processes. The remainder is waste and is returned to the mine for burial or sent to a landfill on the mine property. Quarries do not need or want particle sizes as small as a mine requires.

In a quarry, after crushing, the material is sent over large, vibrating screens which separate the particles by size into different products. The size distribution for a product is typically expressed in percent passing a series of screens, whose opening is expressed in units termed mesh (table 2). The size distribution for a product is referred to as its gradations ('grads' for short). The product size distributions available from each producer vary substantially. Products finer than 8 mesh, often called a manufactured sand, are finer than many operations will produce. However, the crushing process invariably produces a dust-sized material that usually must be captured to meet air pollution standards. Such dust, which is commonly a waste product, is very suitable for many uses of simulant, especially those dominated by mechanical properties.⁸

Quarries working trap rock—basalt, metabasalt, and diabase—are often referred to as 'hard rock' quarries. The stone is very hard and resistant to comminution.

Both mines and quarries are large-scale operations. Quarries producing more than 1 million tons of product a year are common. Most purchasers of quarry products are interested in many thousands of tons at a time. Thus, the purchase of a hundred tons is a small order.

Production techniques used when extracting material from a cinder cone are significantly different compared to either mining or quarrying. The source material does not require drilling, blasting, or crushing. The quarry facility is commonly called a pit or cinder pit. In these operations, there is no need to blast the rock. It is simply scooped up using a front-end loader and passed over vibrating screens, as is done with the crushed rock produced by a quarry. This makes the per ton cost for cinder significantly less than the cost for basalt or metabasalt. It also means that cinder operations do not typically have a product that is finer than 2 mm as a standard product.

Table 2. Approximate mesh to metric conversion table. The two common mesh standards used in the United States are very similar.

Millimeter	Tyler Mesh	US Mesh
4.8	4	4
3.4	6	6
2.4	8	8
2	9	10
1.7	10	12
1.4	12	14
1.2	14	16
1	16	18
0.85	20	20
0.71	24	25
0.6	28	30
0.5	32	35
0.425	35	40
0.355	42	45
0.3	48	50
0.25	60	60
0.212	65	70
0.18	80	80
0.15	100	100
0.125	115	120
0.106	150	140
0.09	170	170
0.075	200	200

As blasting and crushing operations are very energy intensive, the minimum cost for quarry or cinder pit products reflects the cost of energy and the wear and tear on equipment. In the spring of 2013, per ton costs for 200 tons of material produced from hard rock quarries was between \$20 and \$40 per ton at the quarry mouth. Material from cinder pits ranged from \$7 to \$20 per ton. Special run material or processes requiring special handling, such as loading into super sacks, can increase the cost per ton substantially. If the product is a waste or byproduct, such as a dust, the cost may be much lower. Prices for quarry products are quoted based on the customer taking delivery in the quarry or cinder pit.

Once a candidate producer is identified, it is critical to obtain samples of the product. Producers are used to shipping samples as large as a 5-gallon bucket at request. If analyses are done on the material, it is a courtesy to share the results with the producer. Due to health risks, as explained in section 8, the abundance of certain silica phases may need to be checked. The most likely mineral to be present and requiring measurement is quartz. Amorphous silica species and cristobalite may also need to be checked.

Relevant and active quarries east of the Mississippi are exclusively working metabasalts or intrusive rocks. Therefore, they lack vesicular glass, the crystals are larger than is generally desired, and many contain metamorphic minerals. Basalts and volcanic ash/cinder are available in most of the Rocky Mountain states. Metabasalts are also produced in some western areas, especially in California. Section 6 segregates the quarries into basalt and metabasalt producers versus operations in volcanic cinder cones.

6. BASALT AND METABASALT PRODUCERS

Due to the cost of shipping, for Glenn Research Center, Goddard Space Flight Center (GSFC), Kennedy Space Center (KSC), and MSFC, basalt and metabasalt quarries are financially attractive sources of low-cost simulant. Along the Atlantic seaboard, the most southerly quarry producing rock with a potentially useful composition is in Butner, NC, operated by Sunrock. More quarries are found in most of the coastal states to the north of this. Other quarries are found around the western Great Lakes states. There is also a quarry in Missouri operated by Central Stone, near Knob Lick.

There are few producers west of the Mississippi and east of central Colorado. Vulcan Materials operates a major quarry in west-central Texas at Knippa, working a basalt. Starting at the Front Range of the Rocky Mountains and going west, there is a large number of basalt and metabasalt producers.

Potential sources communicated within the search for material by MSFC for the Lunar Surface Testbed are given in sections 6.1 through 6.7.

6.1 Central Oregon Basalt Products, LLC

Scott Andrews
Managing Partner
1747 Mill St.
Madras, OR 97741
Phone: 541-460-3823
scotta@madras.net

This material is a basalt. Samples were provided by the producer. It was tested for MSFC by DCM Science using a modified NIOSH 7500 method and found to have 0.22% quartz.

6.2 Napa Valley Mining Co., LLC

Lat. 45.379709°, Lon. -92.631508°
Karry C. Friendly, C.E.O.
Phone: 425-239-2900
Mark Lipsky
903-316-8519
William Leon Telander
7527 Cashew Drive
Chicago, IL 60462
Phone: 708-444-1066

This material is a metabasalt; the quarry is the Dresser, WI, quarry. Samples were provided by Napa Valley Mining. This product is believed to be the waste fines removed from the aggregate produced by Dresser. The MSDS for the Dresser quarry trap rock states it has a quartz content of 2.27%.

6.3 Reade Advanced Products

Bethany L. Satterfield
V.P./Regional Manager
P.O. Drawer #12820
Reno, NV 89510
Phone: 775-352-1000
bsatterfield@reade.com

They have two quarries, both producing metabasalt. Samples were provided by the producer.

6.4 Sunrock

Lat. 36.115°, Lon. -78.771°
Kenton Richardson
Market Manager Southern Region and Railroad
200 Horizon Drive, Suite 100
Raleigh, NC 27615
krichardson@thesunrockgroup.com
Phone: 919-747-6366
Fax: 919-747-6367

Alternate:
John Tankard
Vice President Plant & Equipment Services
Carolina Sunrock Corporate Headquarters
200 Horizon Drive, Suite 100
Raleigh, NC 27615
Phone: 919-747-6340

Their quarry is in Butner, NC, and produces metabasalt. Samples were provided by the producer. It was tested for MSFC by DCM Science using a modified NIOSH 7500 method and found to have 0.26% quartz.

6.5 Vulcan Materials Company

Lat. 29.285°, Lon. -99.659°
Jeff Johnson
Vulcan Materials—Corporate Office
1200 Urban Center Drive
Birmingham, AL 35242
Phone: 205-298-3000
johnsonj@vmcmail.com

Their quarry is in Knippa, TX. Samples were provided by the producer. The locality is geologically well reported on. An old but useful reference is Lonsdale,⁹ which can be downloaded from <http://www.twdb.state.tx.us/publications/reports/bulletins/doc/Bull.htm/B6212.asp>.

6.6 Central Stone

Lat. 37.681°, Lon. -90.387°
Knob Lick, MO
Contact Randy
Phone: 314-378-4250

No samples were obtained.

6.7 Other Known Producers

The following are producers of basalt known to have at least one product smaller than ¼ inch. These were not contacted during the course of this work. The list was provided by Dr. Greta Orris of the United States Geological Survey (USGS). It is not an exhaustive list.

- **Washington State**

Morrison Gravel
Port Orchard, WA
Phone: 360-876-4701
<<http://www.morrisongravel.com/>>
Randles Sand and Gravel
Puyallup, WA
Phone: 253-531-6800
<<http://randlessandandgravel.net/RSG/>>
EMU Topsoil
Poulsbo, WA
Phone: 360-779-5614
<<http://www.emutopsoil.net/rock.htm>>

- **Oregon**

Mt. Hood Rock

Sandy, OR

Phone: 503-668-5237

<<http://jimturin.com/mthoodrocks/>>

Oldcastle Materials

Several operating companies in the western United States

<<http://www.oldcastlematerials.com/>>

- **California**

Eagle Rock

Contact Sherry

Weaverville, CA

Phone: 530-623-4444

Lyngso

Redwood City, CA

Phone: 650-361-1933

<<http://www.lyngsogarden.com/>>

7. CINDER CONE QUARRIES BY STATE

There are cinder cones in most of the states in the Rocky Mountain region. For creation of the MSFC Lunar Surface Testbed, only sources in New Mexico, Arizona, and Colorado were considered due to shipping costs. Finding candidate producers is not simple. Many cinder pits are small-scale operations compared to quarries in the eastern part of the United States; they do not advertise and they typically do not have any 'Web presence.' Further, the operations are frequently intermittent and seasonal.

The best way to find these producers is to contact specialists interested in volcanology, geologic mapping, or production of industrial minerals, and experienced in a specific locality of interest. Leads to such individuals can be obtained through the State Geological Survey in the individual state. All states have geologic surveys and they are charged with knowing about the geology of the state and assisting production of mineral wealth, <<http://www.stategeologists.org/index.php>>. When contacted, they will be able to provide information based on their own knowledge and recommend useful academic contacts. Each state also maintains records of current, licensed producers of industrial mineral products in the state. Sometimes the authority to do this is in the State Geological Survey. However, as this is normally part of a regulatory process, the records may be elsewhere. In New Mexico, it is in the Mining and Minerals Division, New Mexico Energy, Minerals and Natural Resources Department.

There is considerable variation in the color and standard size distributions available from each producer. Figures 10 and 11 show selected samples photographed against a standard background. Each of the samples is from a producer discussed below. The photos also show there is considerable variation within some samples. This is especially apparent in the materials after washing to remove dust and other fines.

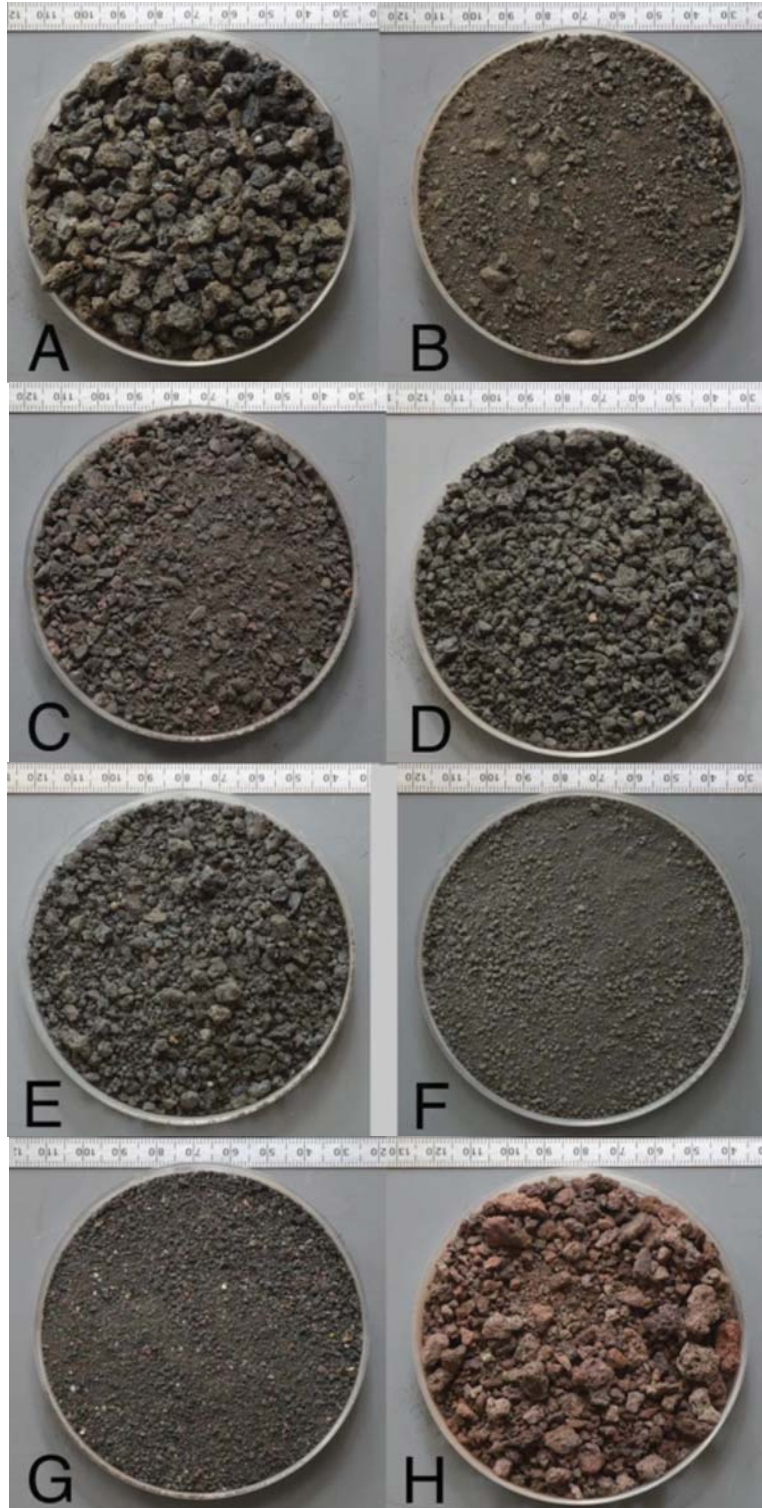


Figure 10. Selected sample of volcanic cinder and ash products; see text for discussion: (A) BTU coarse, (B) BTU fine, (C) Oldcastle, (D) McCoy, CO, (E) Miller Mining coarse, (F) Miller Mining fine, (G) J.E. Wells, and (H) McCoy, CO. Photographs taken outdoors in shade with southern exposure against 18% gray card (produced by Delta 1/CPM, Inc.)

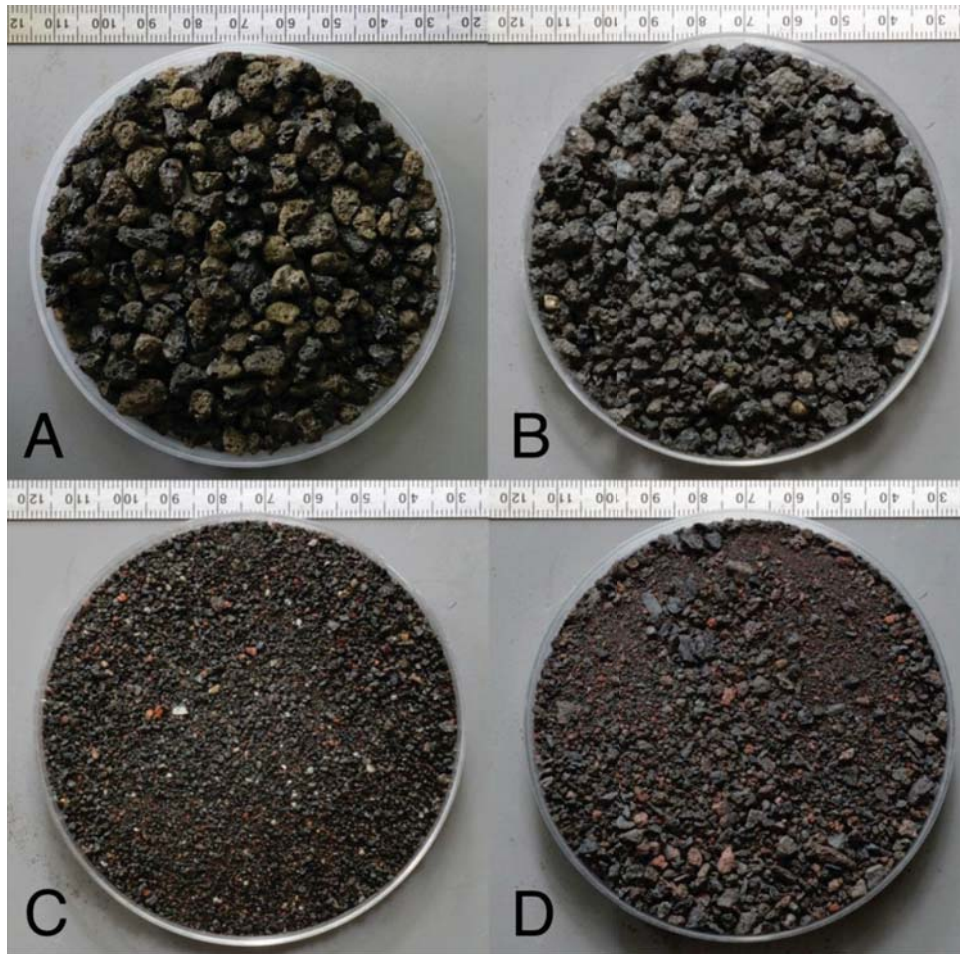


Figure 11. Selected samples after washing with water to remove dust-sized particles and then air dried: (A) BTU coarse, (B) Miller Mining, (C) J.E. Wells, and (D) Oldcastle (millimeter scale). Photographs taken outdoors in shade with southern exposure against 18% gray card (produced by Delta 1/CPM, Inc.)

Figure 12 shows an index map for some producers in Colorado, New Mexico, Arizona, and Texas. Each of the potential sources for a volcanic cinder or ash product considered for the MSFC Lunar Surface Testbed is discussed below. All available and relevant information is retained in this TM.

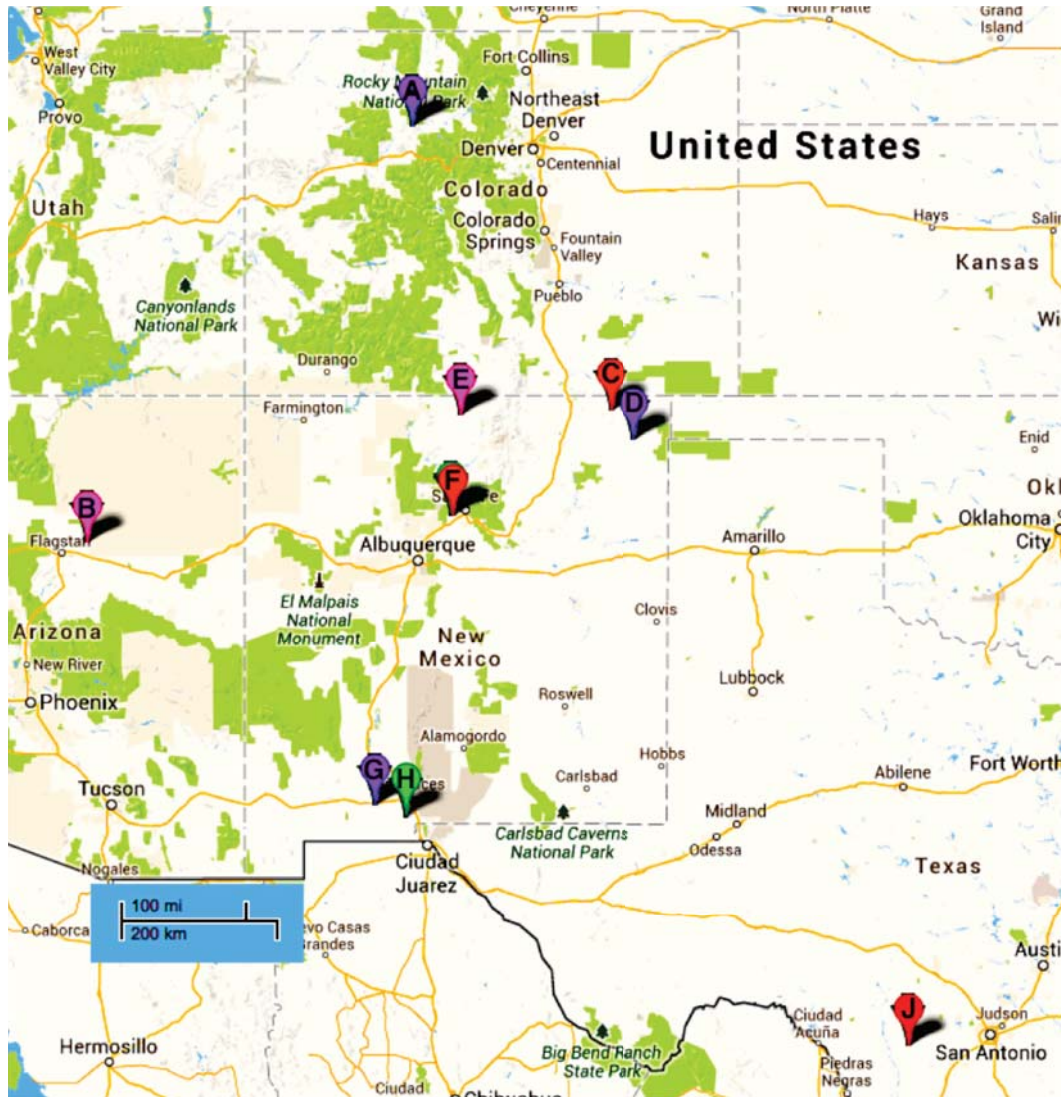


Figure 12. Index map for some producers in Colorado, New Mexico, Arizona, and Texas considered in this TM: (A) Bratton Enterprises, McCoy, CO, (B) Miller Mining and Oldcastle, Flagstaff, AZ, (C) B.T.U. TMR Pit, (D) Cinder Mountain, (E) Red Hill Mine, (F) La Cienega Mine and Cerrito Pelado Mine, (G) Acme Brick, (H) Black Bear Mountain Pit, (J) Knippa, TX (made in Google maps).

7.1 Arizona

7.1.1 Miller Mining, Inc.

Lat. 35.3238°, Lon. -111.2842°

Diana Baires, Office Manager

Miller Mining, Inc.

P.O. Box 31289

Flagstaff, AZ 86003

Phone: 928-526-5700

The pit is near Merriam Crater, northeast of Flagstaff, AZ. It is owned by Robert Miller, 7011 North US Highway 89, Flagstaff, AZ 86004-1111, Phone: 928-526-5757. Miller Mining is associated with Flagstaff Landscape Products, 6500 Old Highway 66 E, Flagstaff, AZ. Figures 13-15 show the location of the Crater/Miller Mining, details of the quarry operation, and mining operation perspective, respectively.



Figure 13. Location of Merriam Crater/Miller Mining, Oldcastle operation and Flagstaff, AZ (from Google Maps).

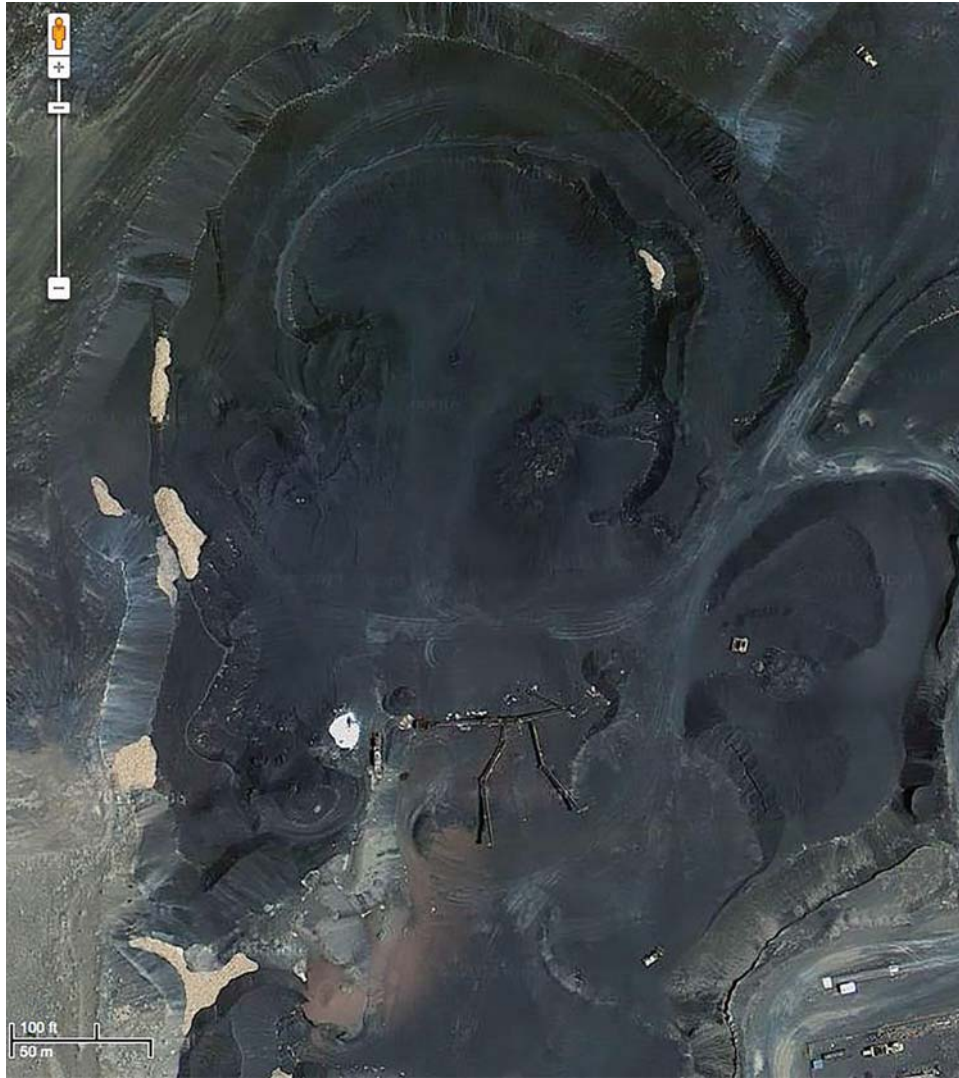


Figure 14. Details of Miller Mining quarry operation at Merriam Crater (from Google Maps).

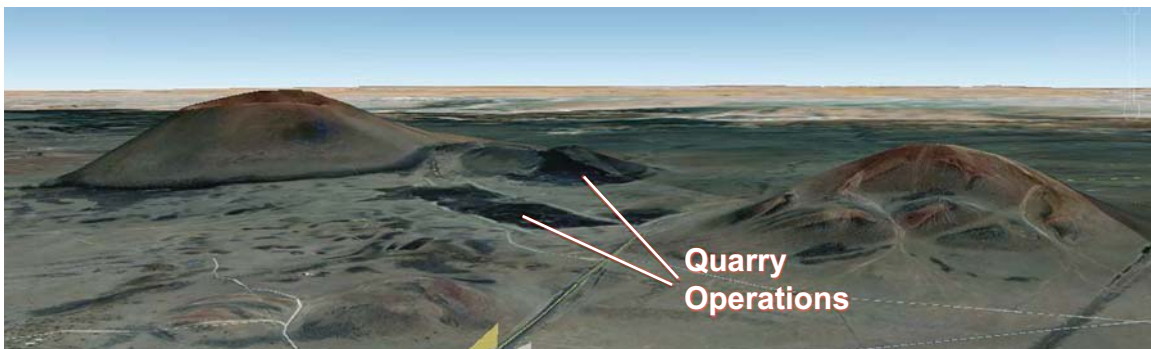


Figure 15. Miller Mining operation perspective looking northeast, no verticle exaggeration (rendered by Google Earth).

This operation has no rail access in the pit. Samples were provided by the producer. The quoted price for the black cinder sand is \$7/ton and the cinder fines is \$60/ton. Table 3 shows the gradations for the two products.

Table 3. Gradations for the two products purchased for the MSFC Lunar Surface Testbed.

Inches and Mesh	Millimeters	Percent Passing	
		Black Cinder Sand	Cinder Fines 'Biosphere'
3/8 in	9.5	100	–
1/4 in	6.3	99	–
4	4.75	92	–
8	2.36	57	100
10	2	48	99
16	1.18	32	87
30	0.6	22	71
40	0.425	18	65
50	0.3	15	56
100	0.15	9	35
200	0.075	5.5	19.6

This is the source of feedstock for the JSC-1 family of simulants. Therefore, compositional information about JSC-1 or JSC-1A applies to this material.

Analysis of the JSC-1AF lunar simulant material for quartz, cristobalite, and tridymite was done by the RJ Lee Group, Inc., 350 Hochberg Road, Monroeville, PA 15146. The technique used was described in their report: “A portion of the sample was ground to a fine powder, mixed with calcium fluoride (CaF₂) as an internal standard, ground further, and back-loaded into a standard XRD holder. The sample was then scanned using standard run parameters on a PANalytical X’Pert Pro XRD unit, equipped with copper radiation. The weight percentage of silica was calculated through the use of the internal standard and calibration coefficients derived from standards NIST 1878a quartz, NIST 1879a cristobalite, and NIOSH/IITRI TY27 tridymite mixed with CaF₂.” Their certified results say there is <0.2% quartz, 0.2% cristobalite, and below detection limit (0.1%) tridymite in JSC-1AF. The quartz concentration was measured at 0.008%.

A chemical analysis of the JSC-1A material done by the USGS is shown in table 4. Figure 16 shows total alkali versus SiO₂ space.

Table 4. Weight percent abundance of major elements and normative mineralogy for JSC-1A.

Oxide	Wt. %	Normative Mineral	Wt. %
SiO ₂	47.1	Quartz	–
TiO ₂	1.87	Orthoclase	5.14
Al ₂ O ₃	17.1	Plagioclase	56.35
Fe ₂ O ₃	3.41	An	50.8
FeO	7.57	Diopside	13.75
MnO	0.18	Olivine	13.79
MgO	6.9	Magnetite	4.97
CaO	10.3	Ilmenite	3.57
Na ₂ O	3.3	Apatite	1.76
K ₂ O	0.86	–	–
P ₂ O ₅	0.76	–	–
Total	99.35	Total	100

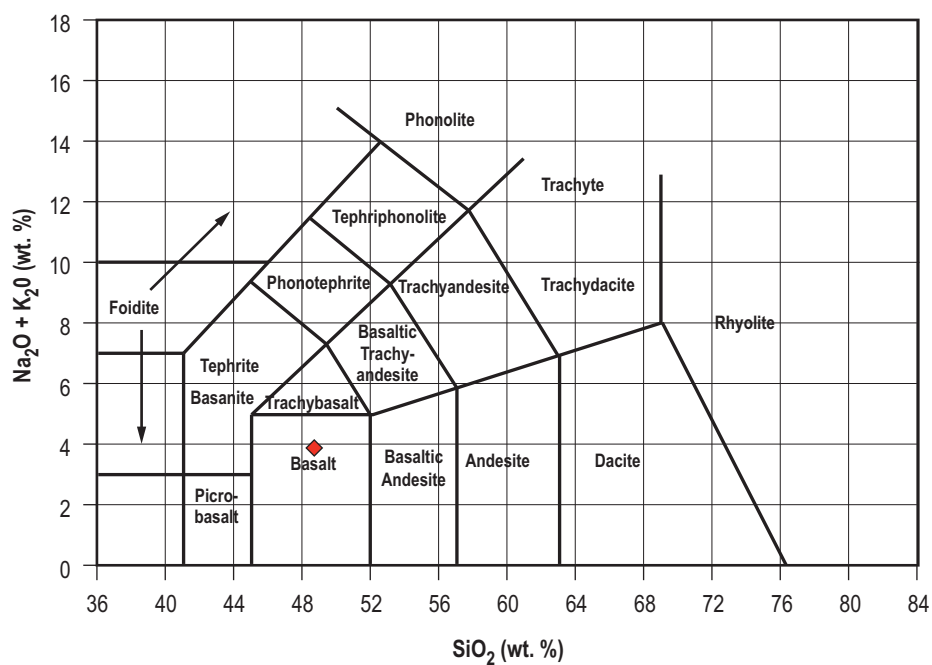


Figure 16. Miller Mining product plotted in total alkali versus SiO₂ space (produced by NAVDAT.org).

7.1.2 Oldcastle

Lat. 35.222°, Lon. -111.409°

East of Flagstaff, AZ, at Sheeps Hill, just north of the Winona exit of I-40.

John Heffernan

Phone: 602-352-3838

Cell: 602-463-5993

John.Heffernan@oldcastle.com

Terry Mitchell

Pit Manager

Phone: 928-607-2387

Terry.mitchell2@oldcastle.com

This operation has rail access in the pit. A sample was provided by the producer. It was concluded this material has too much red coloration for the desired application. Figure 17 gives the operation overview for the Oldcastle pit.



Figure 17. Oldcastle, Sheeps Hill, Flagstaff, AZ, operation overview (from Google Maps).

7.2 New Mexico

The following operations were taken from a list provided by the state of New Mexico. Each instance includes the latitude and longitude of the operation and what contact information is available. Also included are reference images captured from Google Maps. Any analytical information and descriptive information is then included.

7.2.1 B.T.U. TMR Pit

Lat. 36.8182°, Lon. -103.8855°

Buddy Sonchar

B.T.U. Block & Concrete, Inc.

115 Cimarron Ave.

P.O. Box 578

Raton, NM 87740

Phone: 575-445-2373

buddysonch@hotmail.com

This material was deemed satisfactory for the MSFC Lunar Surface Testbed.

This cone is part of the Raton-Clayton volcanic field (fig. 18). Its measured age is 5,200 years old. The cinder cone is northeast of the Capulin Volcano National Monument, on the road between Folsom and Des Moines. There are both red and black cinders in the cone.

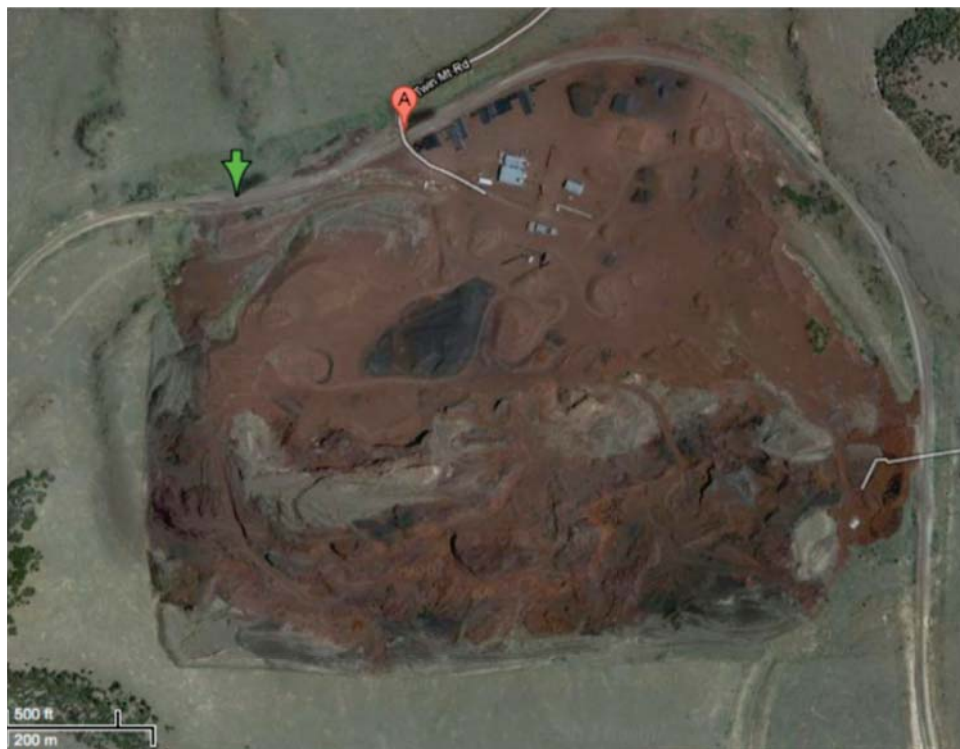


Figure 18. Image of B.T.U. TMR operation (from Google Maps).

The rail access visible in Google images is no longer available. Samples were provided by the producer. The sample obtained has no visibly obvious red coloration. The cinder is extremely vesicular, so much so that many of the larger particles float in water.

The literature clearly states this cone has an unusually high quartz content, possibly due to xenolithic material. These statements need to be checked by careful analysis for quartz and cristobalite, which was not done for this TM. The weight percent oxides and normative mineralogy is shown in table 5. Total alkali versus SiO₂ for the Twin Mountain cone is shown in figure 19.

Table 5. Weight percent oxides and normative mineralogy.
Data from Zhu,¹⁰ sample 855-273, Twin Mountain,
Lat. 36.8217°, Lon. -103.8808°.

Oxide	Wt. %	Normative Mineral	Wt. %
SiO ₂	51.43	Quartz	–
TiO ₂	1.5	Orthoclase	7.58
Al ₂ O ₃	16.44	Plagioclase	56.15
Fe ₂ O ₃	2.38	An	41.6
FeO	7.92	Diopside	11.71
MnO	0.18	Hypersthene	8.76
MgO	6.38	Olivine	8.64
CaO	8.2	Magnetite	3.44
Na ₂ O	3.78	Ilmenite	2.86
K ₂ O	1.28	Apatite	0.91
P ₂ O ₅	0.38	–	–
BaO	0.07	–	–
SrO	0.06	–	–
Total	100	Total	99.96

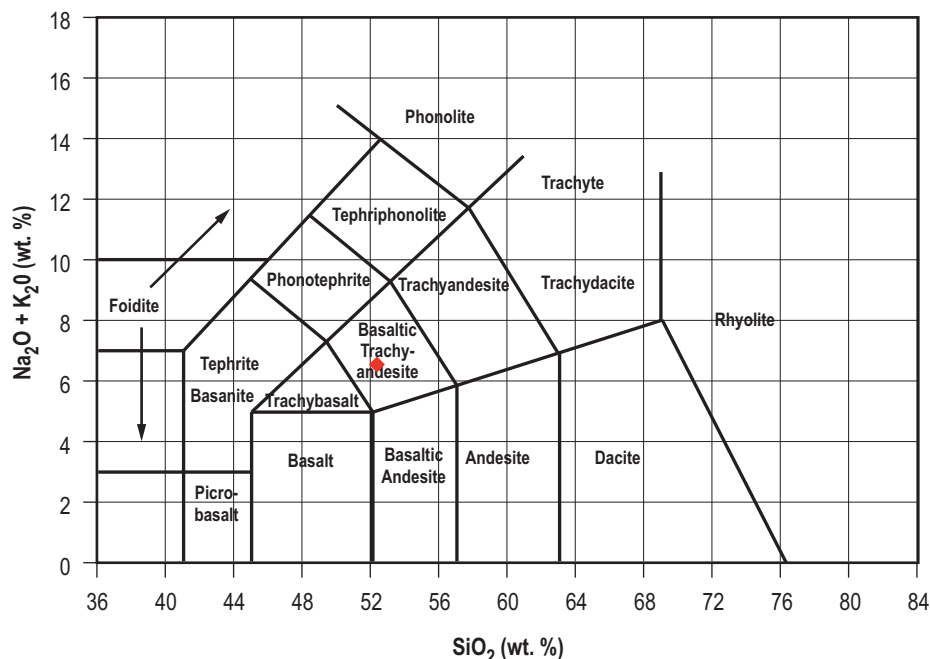


Figure 19. Total alkali versus SiO_2 for the Twin Mountain cone (produced by NAVDAT.org).

The NAVDAT citation for this locality is <http://www.navdat.org/NavdatPortal/GetSample.cfm?sample_id=855-273&georef=1996-063618>. The NAVDAT data are from Zhu and contain minor transcription errors compared to publish dissertation.¹⁰

A sample of the material was analyzed by Dr. Nelia W. Dumbor of the New Mexico Geological Survey. The following is quoted from her report of June 06, 2013.

“This basaltic sample consists of cinders several mm in diameter, along with a crushed split of cinders. The two samples were prepped together. The material in the sample consists of glassy to partially crystalline vesiculated basalt. The range of crystallinity and vesicularity varies from one cinder to the next. In the backscattered electron images (BSE), the brightness of the imaged area depends on the mean atomic number of the imaged material. Much of the imaged material is basaltic glass, which is bright. The black matrix is epoxy. The lathe-like darker grey minerals are plagioclase, which is quite abundant and shows flow alignment in some cinder fragments. Two generations of olivine are also present, an early, large, magnesian olivine (mean atomic number similar to the glass) and a later stage, more Fe rich olivine that are small and bright.”

“Chemical maps for Si, Fe, and K were carried out on one part of the sample (2.5x2.5 mm area). A very small number of Si-rich areas, probably some form of quartz, were recognized (see bright areas on Si map). These were imaged with BSE and found to be small (~5 micron) fragments lodged in vesicles.”

Microprobe analyses of the material done by Dr. Dunbar are given in table 6. Figures 20–33 are from her report.

Table 6. Analyses of B.T.U. cinder (by Nelia Dunbar).

Sample Number	Species	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	BaO	SrO	Cr ₂ O ₃	SO ₂	NiO	F	Cl	Total
1	Plag	50.88	–	29.29	0.67	–	–	13.40	3.56	0.16	–	–	0.11	–	–	–	–	–	98.06
2	Plag	52.69	–	28.5	0.92	–	–	11.83	4.36	0.26	–	0.02	0.13	–	–	–	–	–	98.69
3	Olivine	38.89	0.03	–	21.2	0.23	40.53	0.22	–	–	–	–	–	0.03	–	0.1	–	–	101.22
4	Olivine	39.02	0.05	–	20.76	0.27	41.09	0.3	–	–	–	–	–	0.06	–	0.09	–	–	101.63
5	Plag	52.71	–	28.34	0.74	–	–	12.04	4.31	0.23	–	0.04	0.14	–	–	–	–	–	98.55
6	Plag	51.33	–	29.58	0.7	–	–	13.25	3.7	0.16	–	–	0.14	–	–	–	–	–	98.85
7	Glass	51.56	1.55	16.29	10.41	0.26	5.07	8.6	3.8	1.28	0.39	–	–	–	0.03	–	–	0.03	99.27
8	Glass	51.85	1.68	16.01	10.48	0.19	4.86	8.45	3.69	1.3	0.42	–	–	–	0.04	–	0.26	0.04	99.26
9	Glass	51.54	1.57	16.58	10.27	0.21	5.18	8.65	3.86	1.37	0.44	–	–	–	0.04	–	0.13	0.03	99.87
10	Glass	52.15	1.49	16.8	9.98	0.18	4.95	8.52	3.68	1.31	0.46	–	–	–	0.02	–	0.19	0.04	99.77
11	Glass	52.34	1.57	16.52	10.13	0.19	4.93	8.3	4.02	1.45	0.46	–	–	–	–	–	–	0.03	99.94
12	Glass	52.22	1.63	16.62	10.31	0.19	5.09	8.54	3.05	1.37	0.44	–	–	–	0.02	–	0.04	0.03	99.57
13	Glass	51.48	1.52	16.53	10.36	0.22	5.04	8.73	3.5	1.28	0.47	–	–	–	0.02	–	0.18	0.02	99.37
14	Glass	52.09	1.57	16.70	9.99	0.2	5.10	8.68	3.28	1.32	0.39	–	–	–	0.01	–	–	0.04	99.35
15	Glass	51.6	1.63	16.26	11.14	0.16	4.84	8.51	3.41	1.3	0.52	–	–	–	0.05	–	0.09	0.02	99.54
16	Glass	53.27	1.59	16.4	10.15	0.2	4.93	8.11	2.71	1.64	0.46	–	–	–	–	–	–	0.05	99.49
17	Olivine	38.37	0.04	–	23.26	0.32	38.84	0.26	–	–	–	–	–	0.01	–	0.08	–	–	101.19
18	Olivine	38.76	0.01	–	21.38	0.3	40.69	0.28	–	–	–	–	–	0.02	–	0.1	–	–	101.54
19	Olivine	37.72	0.1	–	26.14	0.38	35.53	0.43	–	–	–	–	–	0.02	–	0.06	–	–	100.38
20	Olivine	37.73	0.07	–	26.16	0.33	36.36	0.44	–	–	–	–	–	0.06	–	0.07	–	–	101.23
21	Plag	53.97	–	27.45	0.99	–	–	11.26	4.79	0.28	–	–	0.18	–	–	–	–	–	98.92
22	Plag	52.6	–	28.25	1.19	–	–	11.99	4.19	0.23	–	0.04	0.19	–	–	–	–	–	98.66
23	Plag	53.31	–	24.56	3.86	–	–	10.36	4.46	0.64	–	–	0.12	–	–	–	–	–	97.32
24	Glass	52.21	2.06	14.53	11.67	0.12	4.4	8.14	4.05	1.75	0.51	–	–	–	0.03	–	0.17	0.04	99.69
25	Glass	52.23	1.9	14.77	11.56	0.17	4.24	8.31	3.99	1.62	0.55	–	–	–	0.03	–	0.08	0.05	99.51

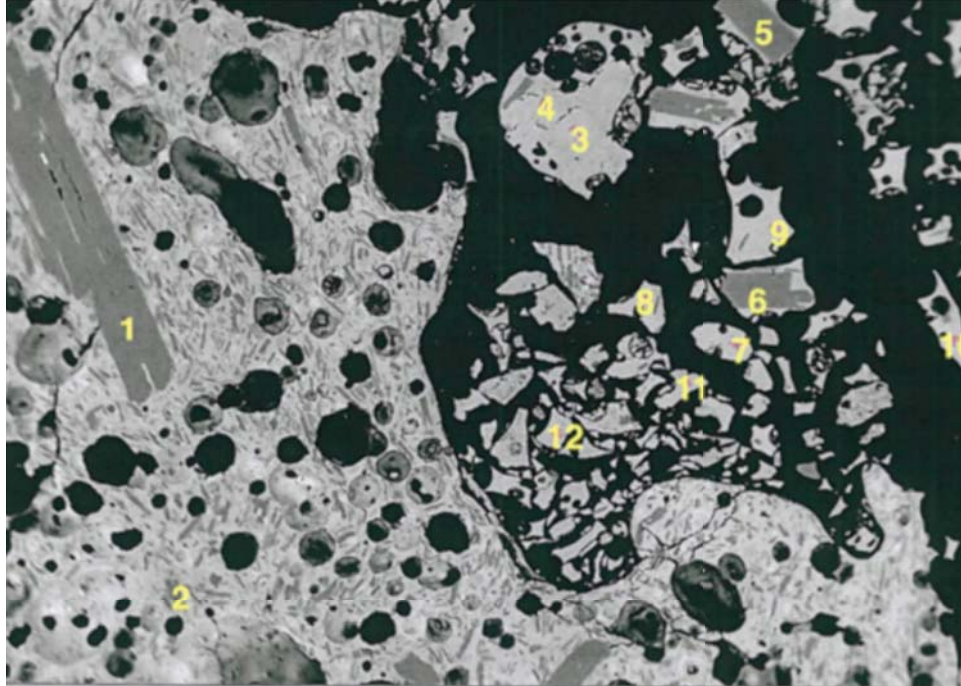


Figure 20. Index of sample points probed and illustrative textures of B.T.U. cinder. Shows partially crystalline cinder as well as glassier crushed cinders (BSE image).

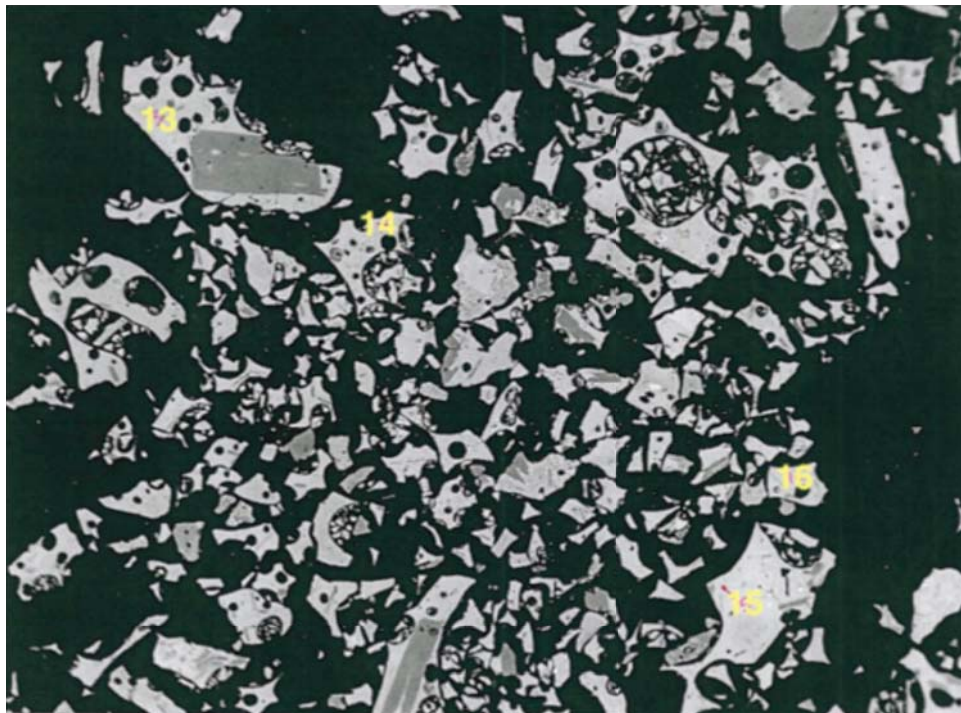


Figure 21. Index of sample points probed and illustrative textures of crushed cinder fragments from the B.T.U. pit (BSE image).

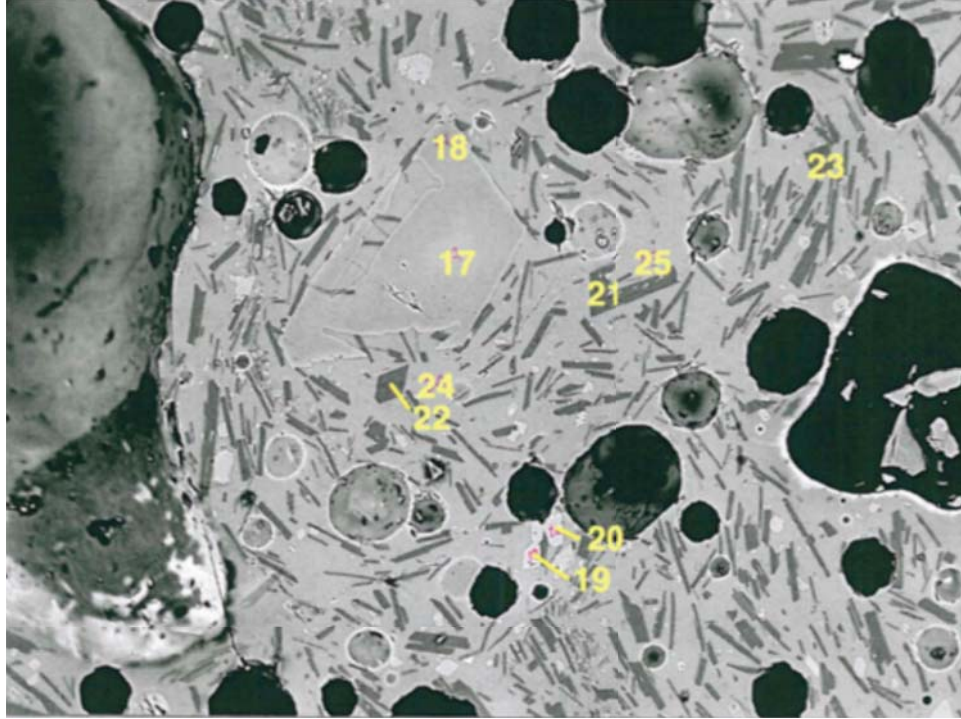


Figure 22. Index of sample points probed and detail from figure 18 illustrative textures of B.T.U. cinder. Blowup of figure 26 showing phenocrysts (BSE image).

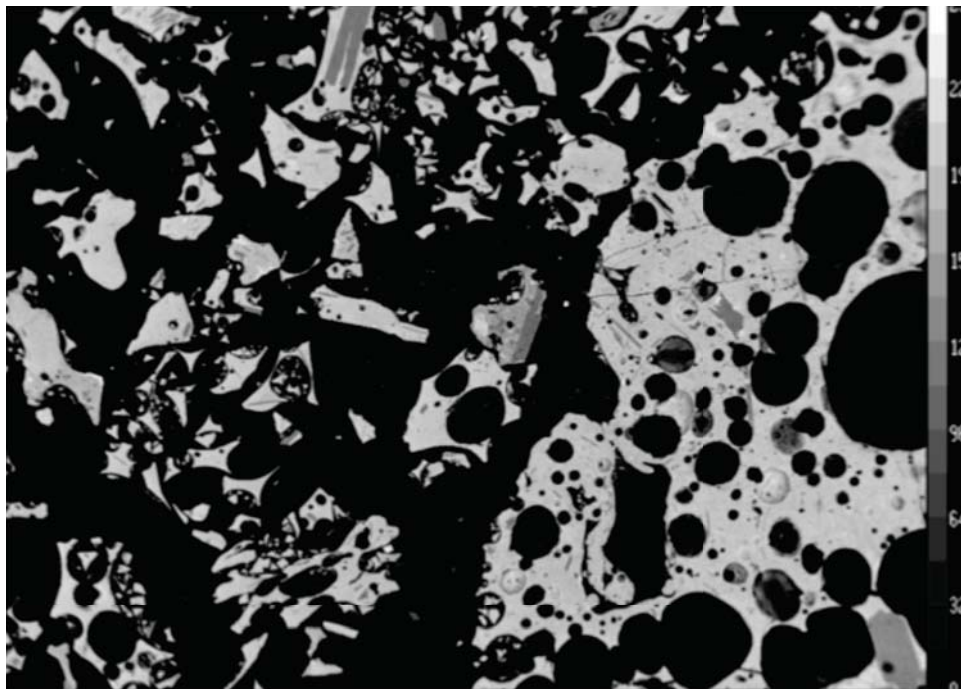


Figure 23. Glassy cinder fragments (BSE image).

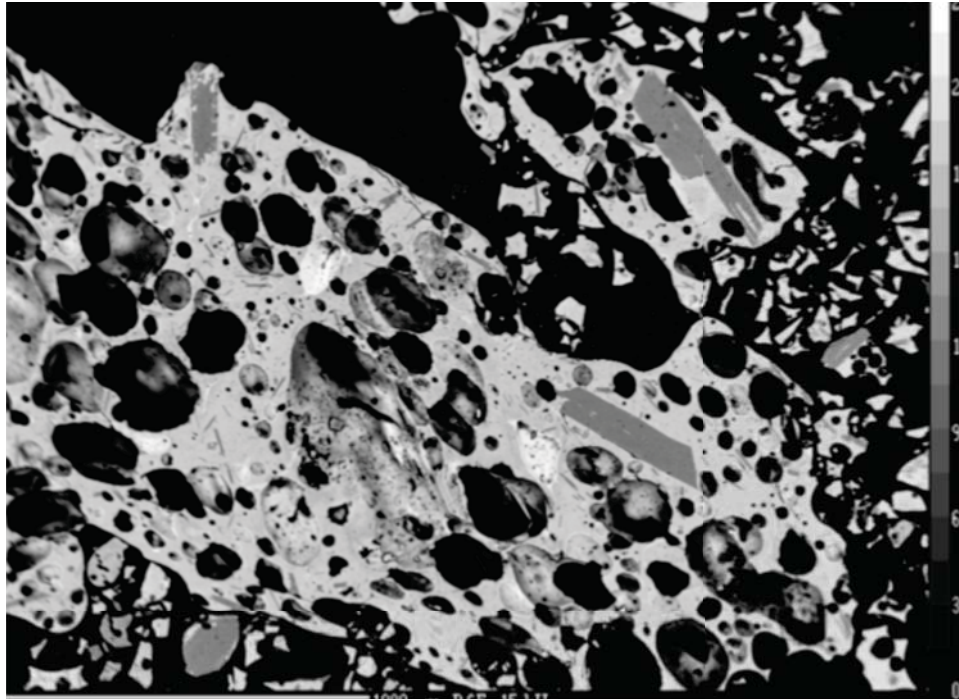


Figure 24. Large vesiculated fragment (BSE image).

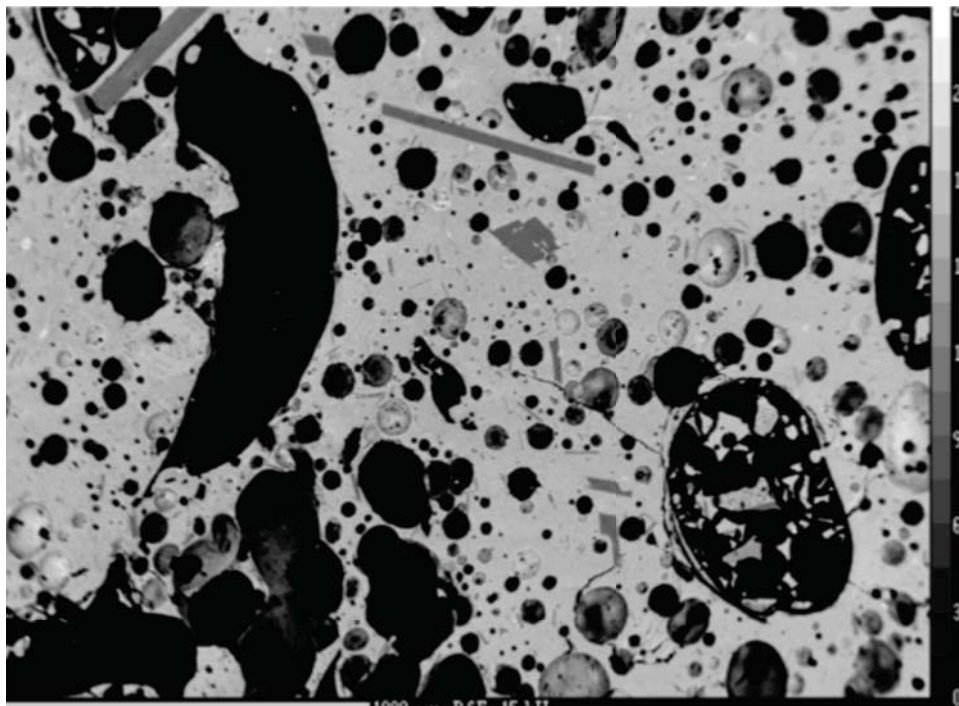


Figure 25. Denser, lower vesicularity fragment (BSE image).

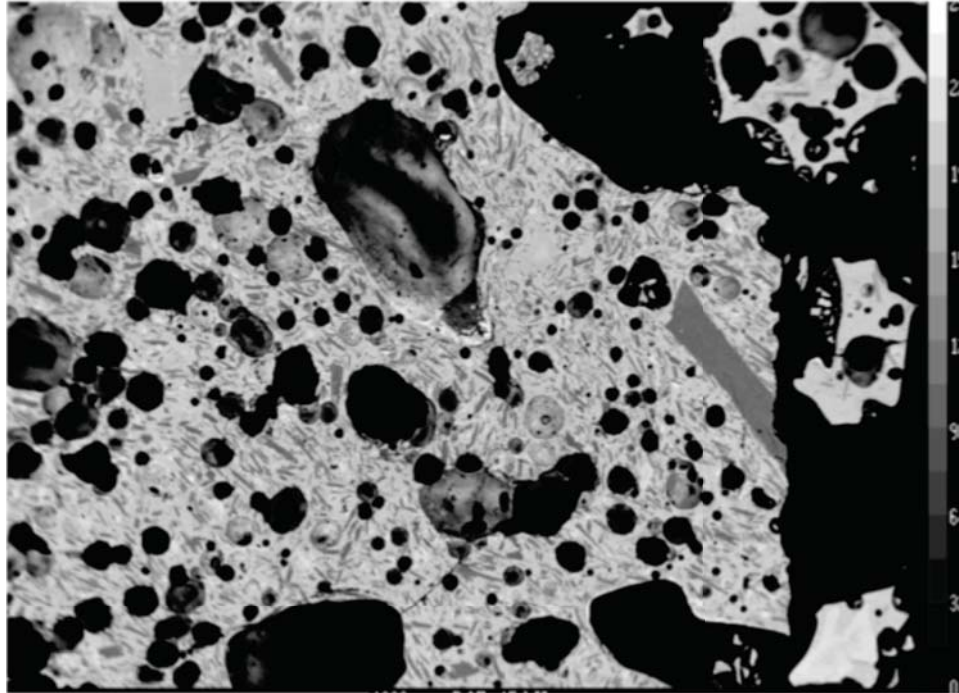


Figure 26. Vesicular fragment with flow alignment of plagioclase (BSE image).

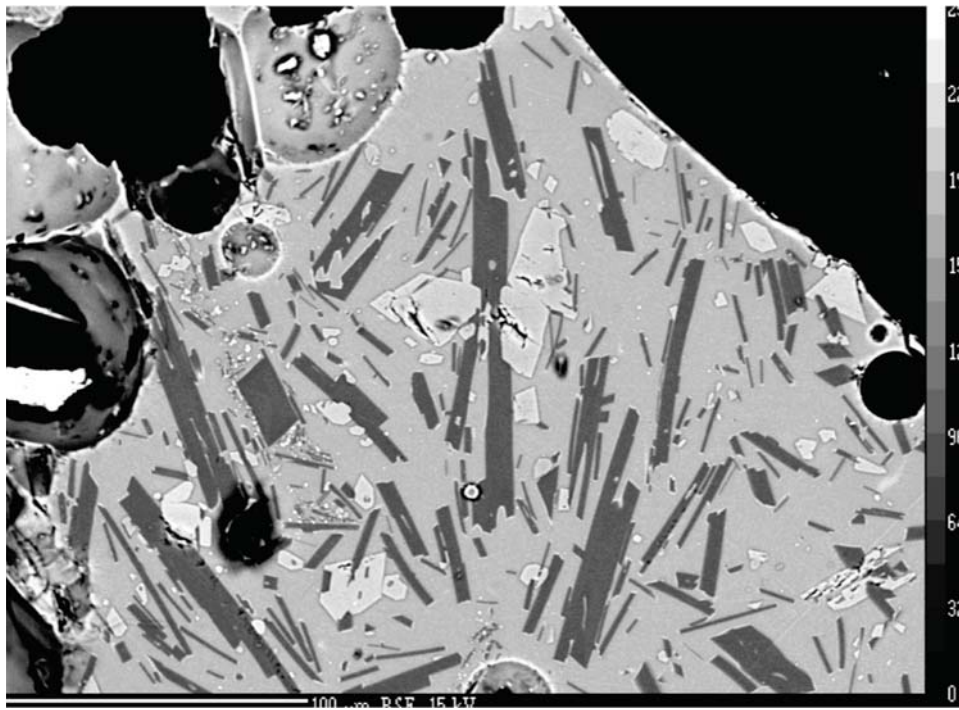


Figure 27. Moderately crystalline cinder fragment (BSE image).

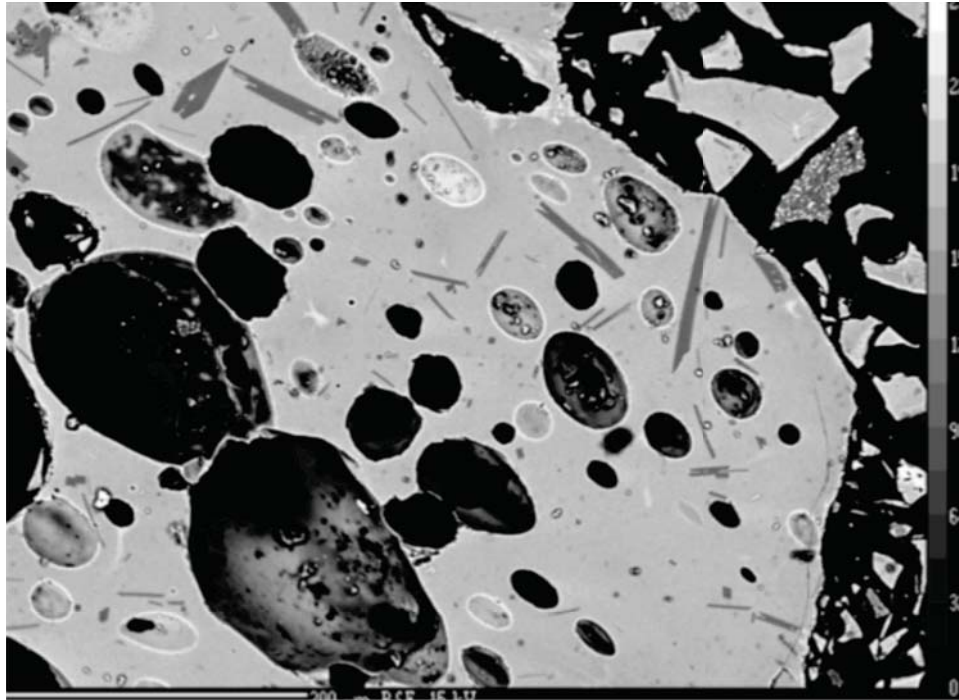


Figure 28. Low crystalline cinder fragment (BSE image).

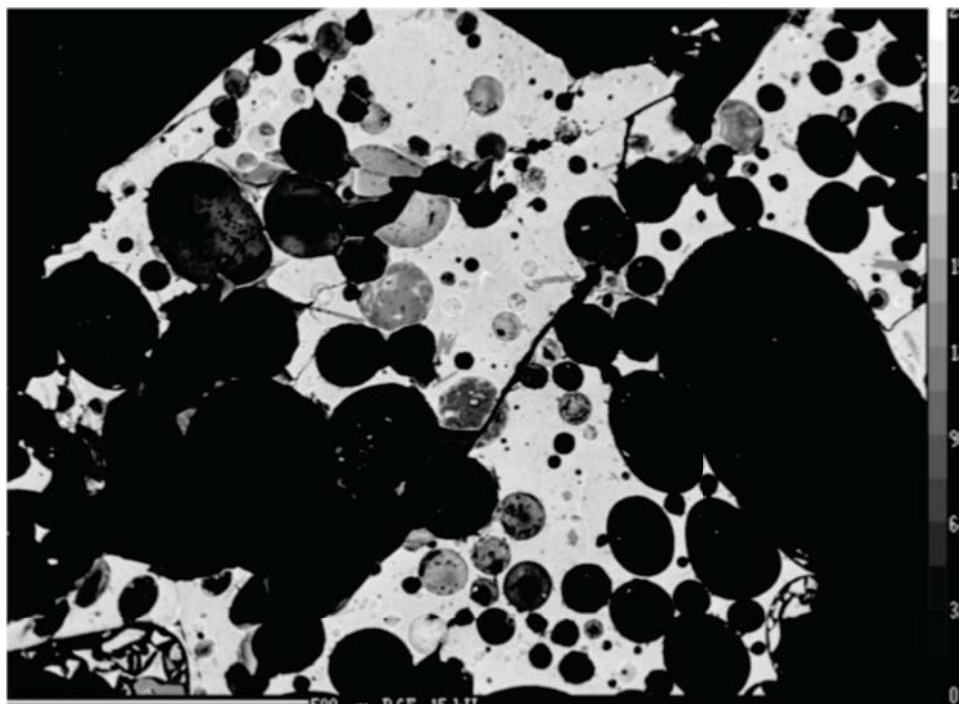


Figure 29. Low crystalline, high vesicularity cinder (BSE image).

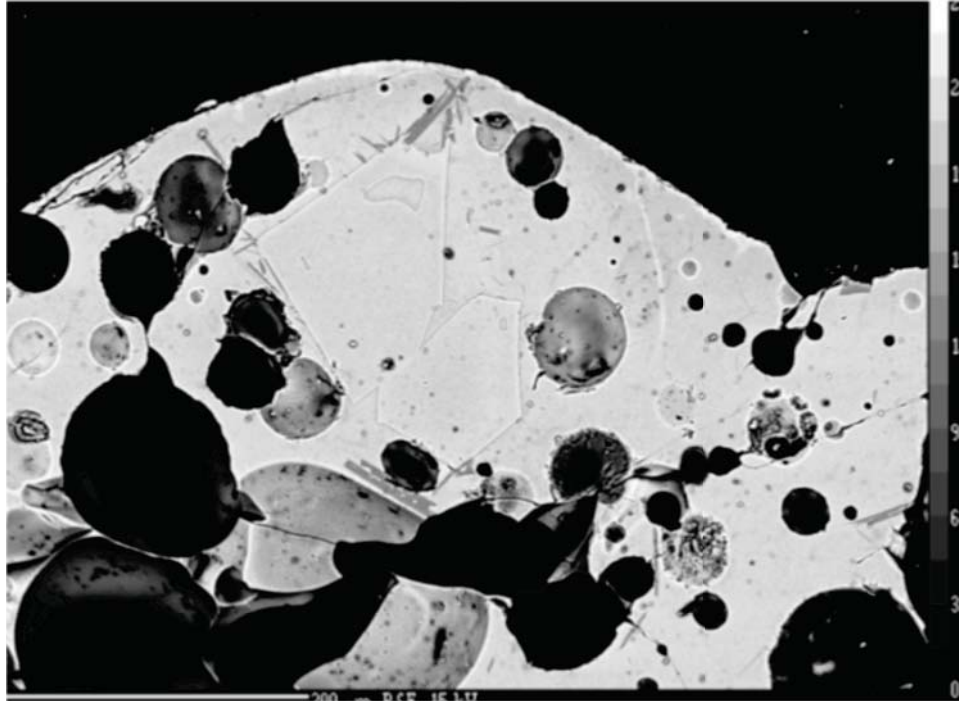


Figure 30. Two large olivine in mostly aphyric glass (BSE image).

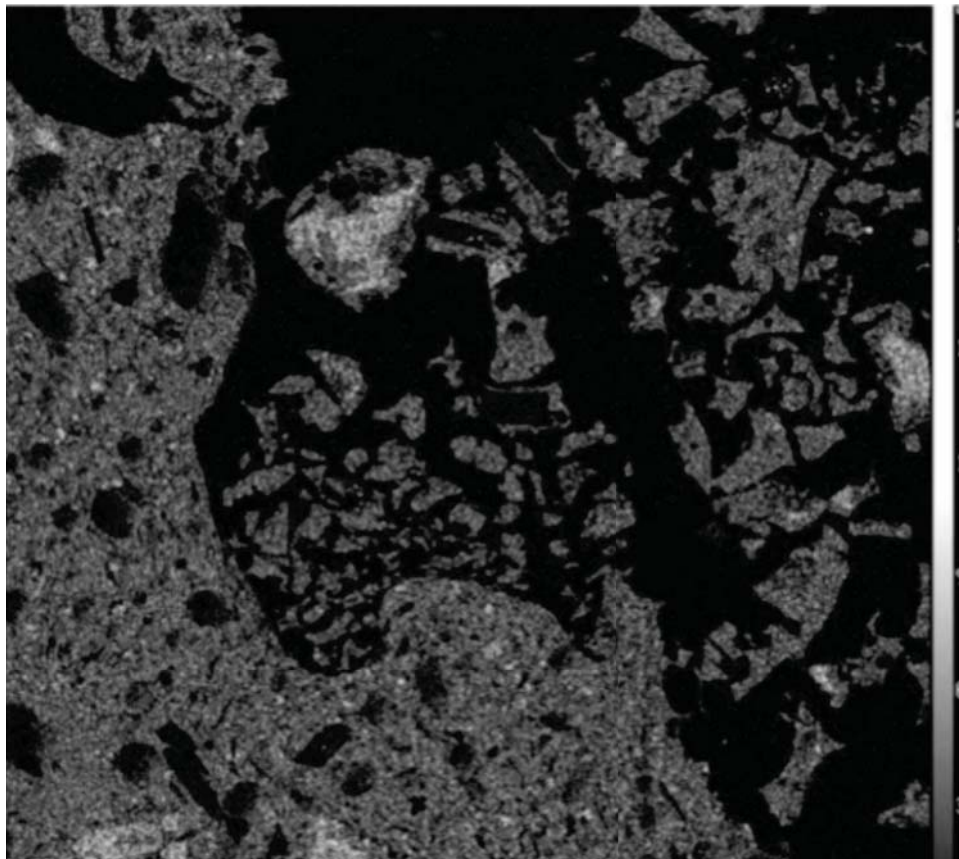


Figure 31. Iron abundance based on the $K\alpha$ line (compare fig. 20).

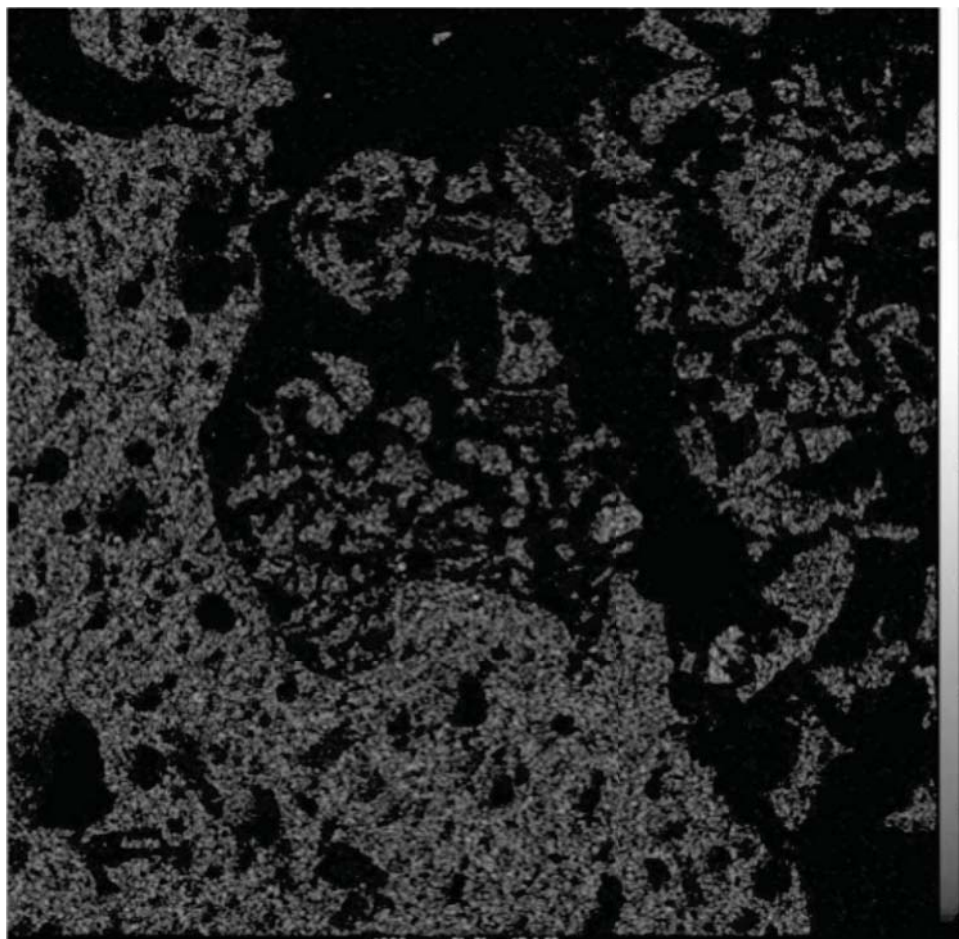


Figure 32. Potassium abundance based on the $K\alpha$ line (compare fig. 20).

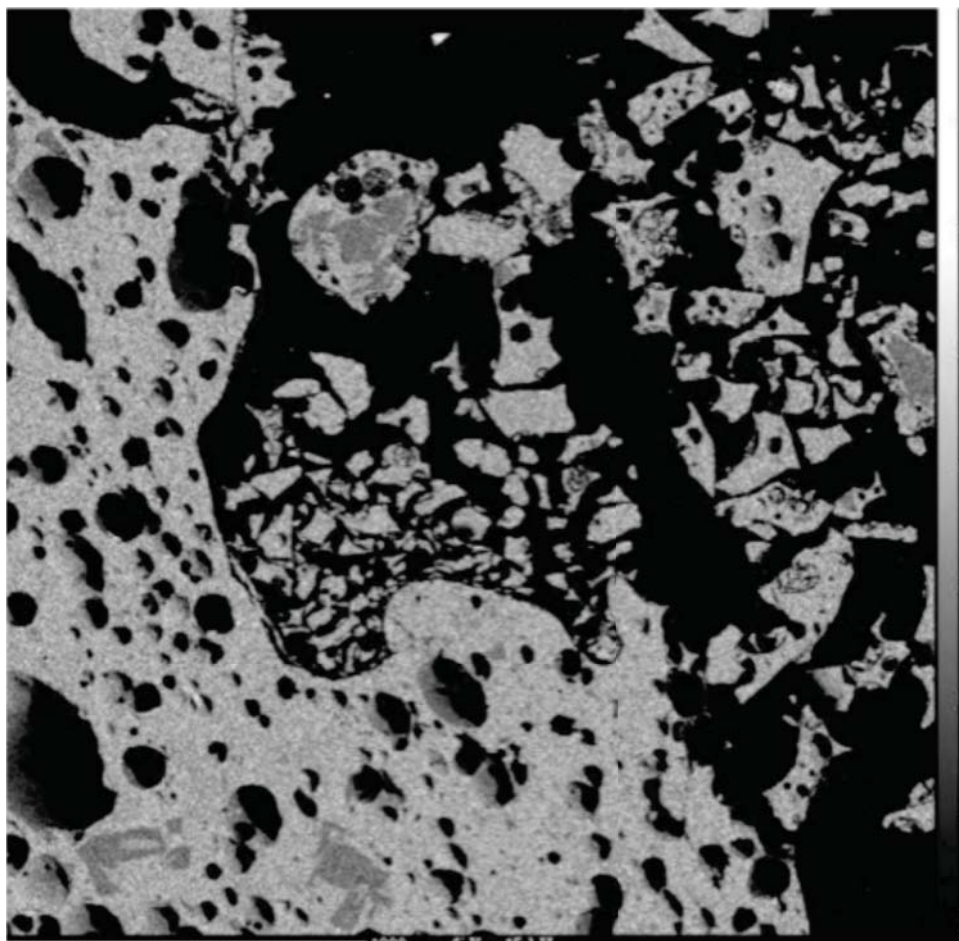


Figure 33. Silicone abundance based on the $K\alpha$ line (compare fig. 20).

7.2.2 Black Bear Mountain Pit

Lat. 32.07°, Lon. -106.79°
Del Norte Masonry Products, Inc.
4560 Ripley Dr.
El Paso, TX 79922
Phone: 915-584-4453

There is no rail access in the pit.

According to Kay Backer, the land is owned by the BLM. Under the terms of their agreement with Del Norte, the company cannot sell the cinder. They can only use it in their own product. A sample of this material was not obtained.

The cone pictured in figure 34 is part of the Potrillo volcanic field.



Figure 34. Black Bear Mountain Pit (from Google Maps).

7.2.3 Cerrito Pelado Mine

Lat. 35.65°, Lon. -106.15°
Pavestone, LLC
North American Marble Division
229 Industrial Park Rd.
Cartersville, GA 30121
Phone: 770-607-3345

A sample of this material was not obtained. This material is red and therefore not suitable for a general-purpose lunar simulant (fig. 35).



Figure 35. Cerrito Pelado Mine (from Google Maps).

7.2.4 Cinder Mountain Pit

Lat. 36.50°, Lon. -103.55°
Volcanic Stone Company
1553 FM 2203
Dumas, TX 79029
Phone: 806-935-6966

There is no rail access in the pit.

Part of the Raton-Clayton volcanic field is shown in figure 36. This site does not have an entry in NAVDAT. Samples of this material were not obtained. It would be advisable for samples to be obtained and analyzed in the future as this is the eastern-most cinder pit in the western United States and it may have a black/grey cinder.



Figure 36. Cinder Mountain Pit (from Google Maps).

7.2.5 La Cienega Mine

Lat. 35.62°, Lon. -106.14°
Crego Block
6140 2nd Street NW
Albuquerque, NM 87107
Phone: 505-850-3982

A sample of this material was not obtained. This material is red and therefore not suitable for a general-purpose lunar simulant. See figure 37.

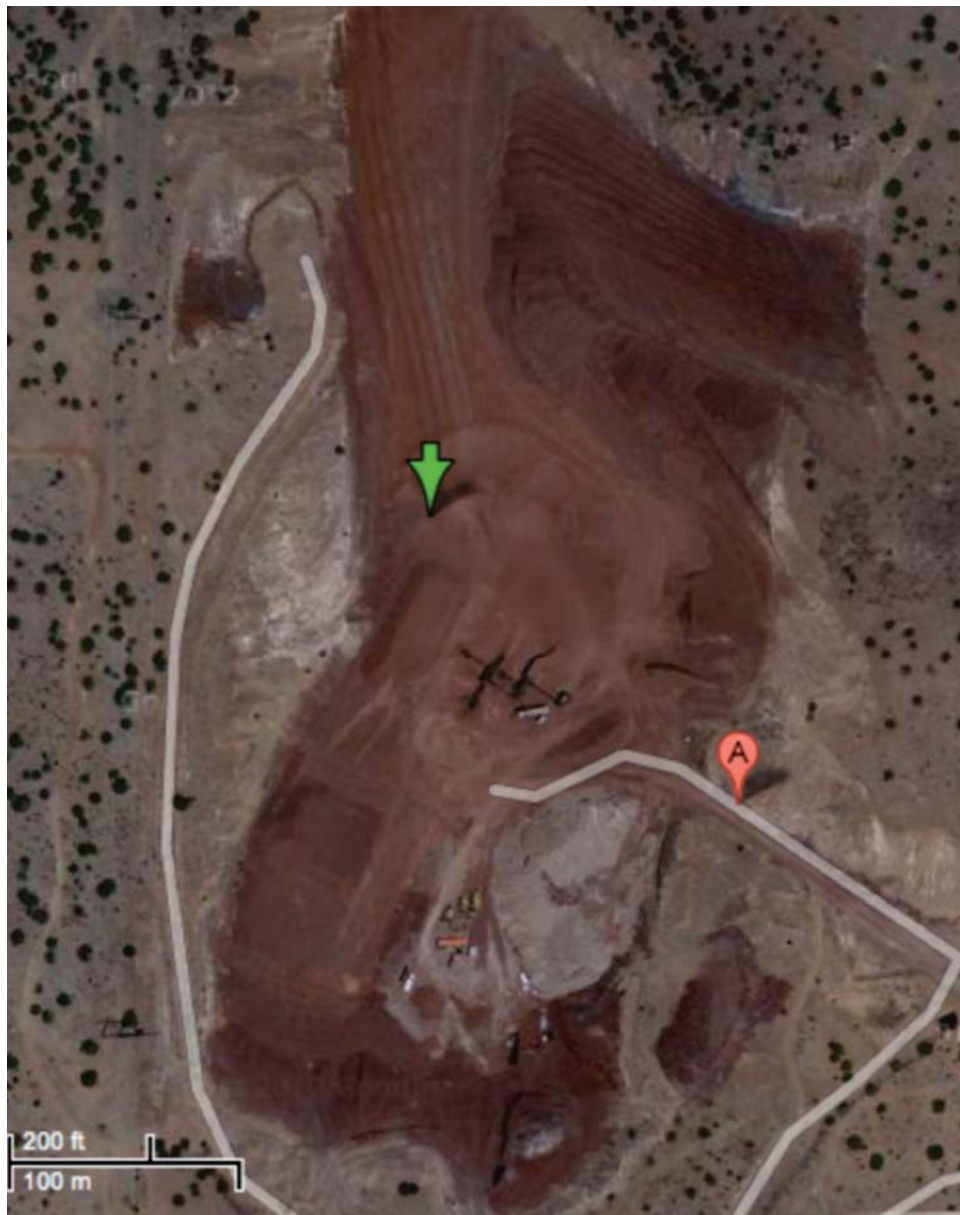


Figure 37. La Cienega Mine (from Google Maps).

7.2.6 Red Hill Mine

Lat. 36.77°, Lon. -106.01°

Colorado Lava, Inc.

P.O. Box 151

Milan, IL 61264

Phone: 800-528-2765

A sample of this material was not obtained. This material is red and therefore not suitable for a general-purpose lunar simulant. See figure 38.



Figure 38. Red Hill Mine (from Google Maps).

7.2.7 Acme Brick

Lat. 32.2211°, Lon. -107.2305°
Part of the Potrillo Volcanic Field
Acme Brick (used to be FeatherLite)
El Paso, TX
Contacts:
Don Welch or Steve Bush
Phone: 915-859-9171
Ysai, Production Manger
Phone: 915-471-1799

A sample of this material was requested but not obtained.

The NAVDAT entry for this location is <http://www.navdat.org/NavdatPortal/GetSample.cfm?sample_id=882&georef=2006-083239>. The age given for the cone is 40,000 years. Figure 39 shows the Acme Brick volcanic field. Table 7 shows the normative mineralogy weight percent for the cinder cone. Total alkali versus SiO₂ is shown in figure 40.



Figure 39. Acme Brick (from Google Maps).

Table 7. Weight percent oxides and normative mineralogy for Acme Brick cinder cone (from NAVDAT.org).

Oxide	Wt. %	Normative Mineral	Wt. %
SiO ₂	45.06	Quartz	–
TiO ₂	2.81	Orthoclase	11.41
Al ₂ O ₃	15.75	Plagioclase	28.13
Fe ₂ O ₃	12.16	An	61.2
MnO	0.19	Diopside	20.06
MgO	8.6	Hypersthene	–
CaO	9.64	Olivine	15.48
Na ₂ O	4.37	Magnetite	3.51
K ₂ O	1.94	Ilmenite	5.32
P ₂ O ₅	0.8	Apatite	1.85
Total	101.32	Total	99.99

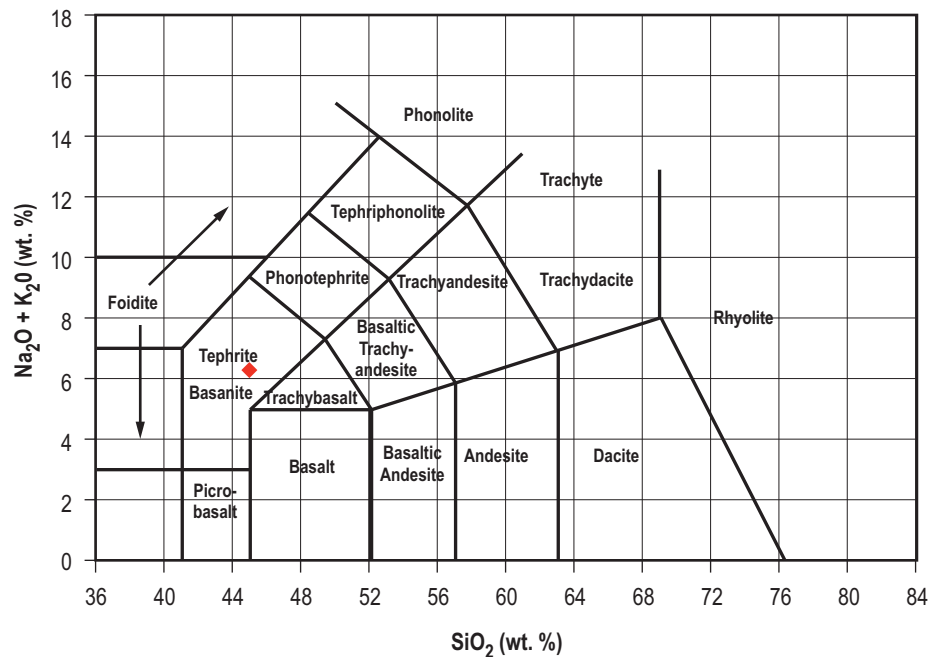


Figure 40. Total alkali versus SiO₂ for the Acme Brick cinder pit (produced by NAVDAT.org).

7.2.8 J.E. Wells

Las Cruces, NM
Phone: 575-496-4503

Mr. Wells buys and sells volcanic cinder products nationwide. A sample of material was received and judged to have more red and white flecks than are desirable. His operation is at the intersection of W. Amadore and Compress Rd. in Las Cruces. He was unwilling to specify the exact location of his source.

7.3 Colorado

7.3.1 McCoy, Colorado

Lat. 39.9720°, Lon. -106.7032°
Jim Bratton, owner, resident of Yampa, CO
Bratton Enterprises
3333 Conger Mesa Rd.
McCoy, CO 80463
Phone: 970-653-4345
Contact: Travis

They do have rail access through UP. The finest sized product is 3/8 inch or less, and is \$8.50/ton. They have both black and red products. Samples were obtained from the producer. The McCoy cinder pit is shown in figure 41. Figure 42 gives total alkali versus SiO₂ for the McCoy cinder pit.



Figure 41. Bratton Enterprise, McCoy, CO, cinder pit (from Google Maps).

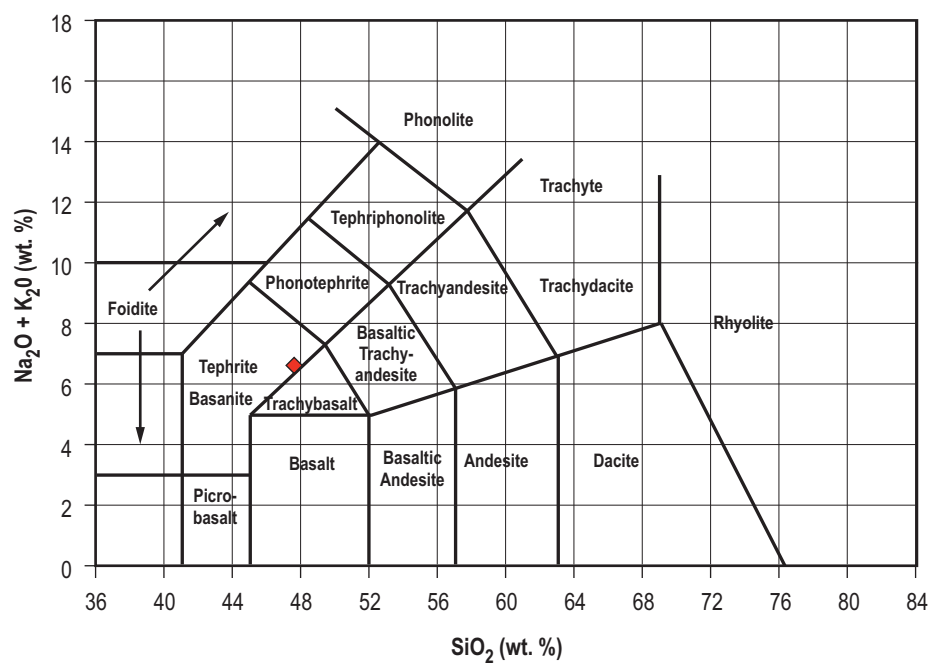


Figure 42. Total alkali versus SiO_2 for the McCoy, CO, cinder pit (produced by NAVDAT.org).

The reference in NAVDAT for this cone is <http://www.navdat.org/NavdatPortal/Get-Sample.cfm?sample_id=US111&georef=1989-064162>. The age given there for the cone is 640,000 years, which is from Larson et al.¹¹ Table 8 shows weight oxides and normative mineralogy.

Table 8. Weight percent oxides and normative mineralogy (from NAVDAT.org).

Oxide	Wt. %	Normative Mineral	Wt. %
SiO ₂	47.78	Quartz	–
TiO ₂	1.86	Orthoclase	15.07
Al ₂ O ₃	16.03	Plagioclase	31.95
Fe ₂ O ₃	10.91	An	47.1
FeO	–	Diopside	16.98
MnO	0.166	Olivine	13.05
MgO	6.47	Magnetite	3.19
CaO	9.13	Ilmenite	3.57
Na ₂ O	4.09	Apatite	2.41
K ₂ O	2.53	–	–
P ₂ O ₅	1.03	–	–
Total	100	Total	100

8. SOURCES OF INFORMATION AND SERVICES

8.1 Analyses

Materials considered for purchase may need to be characterized for various parameters. One of the parameters of major interest is the content of respirable hazardous silicone dioxide (SiO_2) mineral phases. As noted in a subsequent section, this analysis presents specialized problems when dealing with basaltic geologic materials. It is strongly recommended that any analysis for quartz or cristobalite be done by a certified laboratory knowledgeable about and able to deal with these problems. The contact information for one such lab is:

DCM Science Lab
Ron Schott, Lab Director
12421 W. 49th Ave., Unit #6
Wheat Ridge, CO 80033
Phone: 800-852-7340

The method they use is a modification of the NIOSH 7500 technique. The sample is attacked by phosphoric acid according to a specific protocol. This removes much of the ‘matrix’ material, concentrating the quartz. Their fees for this analysis are as follows:

- Bulk silica with phosphoric treatment (quartz)
\$260 per sample
\$40 each additional polymorph, per sample, if necessary
- Respirable fraction with phosphoric treatment (quartz)
\$315 per sample
\$40 each additional polymorph, per sample, if necessary.

8.2 Geology

Cinder cones are normally part of large features called volcanic fields. For example, the San Francisco Volcanic Field (SFVF), of which Merriam Crater is a part, covers 4,700 km² and contains 600 volcanoes. The age of the volcanoes in the SFVF ranges from almost 6 million years old to less than 1,000 years old. While volcanoes in a specific volcanic field usually have many similarities, each cone in a volcanic field is compositionally distinct. Therefore, it is important to get specific information about specific deposits.

Finding any technical information about specific cones is generally difficult. Cinder pits are small-scale operations compared to many hard rock quarries; and, there tends to be little technical literature specific to individual producers. If there is published information about a local, it is likely, but not always, to be found in the Western North American Volcanic and Intrusive Rock Database, NAVDAT <<http://www.navdat.org/>>.

To learn about the geology of a deposit, as discrete from locating producers, directly contacting all the universities in the state that have departments of geology or earth sciences is useful. These are readily found by doing an Internet search. Not all departments will have anyone with an interest relevant to the search. However, they frequently will know who probably does and can direct the effort appropriately.

The USGS can also be a very useful source of information. Their relevant interests arise from several mandates. First, they have active geologic mapping programs, and the individuals engaged in this must become highly knowledgeable about the regions in which they work. Second, like the state surveys, they are charged with assisting in the economic production of geologic resources. Finally, they have active research programs in which volcanology is a significant element. As the USGS is a large organization, it can be difficult to find the correct person to start with. Unless one has personal contacts inside the Survey, it is probably prudent to begin with the second point, industrial mineral production.

9. NOTES ON THE HEALTH RISKS OF CRYSTALLINE SILICA

Simulant materials may represent a health risk if the particles are small enough or it contains any of several ‘silica’ phases. There are two ways to mitigate the potential risk. The first is to use material with particles large enough not be hazardous. The second way is to select material that does not contain hazardous phases. As the abundance of hazardous phases cannot be predicted with sufficient certainty, as has been demonstrated with experience with the BP-1 simulant, it is important to actually measure the abundances using a certified lab.

Such analyses, as done on simulant materials, is complicated by the composition of basaltic rocks. The most common analytical techniques for these measurements use x-ray diffraction (XRD). Unfortunately, the most abundant mineral species in basalts is plagioclase, has diffraction lines that overlap the diffraction lines for quartz and cristobalite. This interference makes accurate measurement of these two minerals much more difficult, especially in low concentrations. This problem can be handled by various methods. It is important that, however the analysis is done, this interference is properly allowed for.

The following is a detailed statement about the health risk associated with particulates containing ‘silica’ phases:

SiO₂ is widely found in both nature and manufactured products. It is commonly referred to as ‘silica,’ which unfortunately is a term also used to describe other things. For a good discussion of this point, see Branch of Industrial Minerals Staff, 1992, *Crystalline Silica Primer*.¹² Naturally occurring crystalline materials are termed ‘minerals’ and each mineral is given a name. A mineral has a specific range of elemental composition and the atoms are in specific spatial patterns. The minerals of interest for this discussion are the crystalline SiO₂ phases named quartz, cristobalite, and tridymite. For this discussion, the microcrystalline, also known as cryptocrystalline, forms of quartz, such as chalcedony and chert, are considered the same as quartz. There are other polymorphs of crystalline SiO₂, but they are not likely to occur in materials of interest for the MSFC Test Bed Facility. A list of synonyms for crystalline and amorphous quartz are included in sections 9.4 and 9.5.

Specific health risks are known to exist for SiO₂ that is either crystalline or amorphous, i.e., lacking a regular, repeating pattern of atoms. One risk is related to cancer; the other is related to a disease termed ‘silicosis.’ According to the International Agency for Research on Cancer (IARC) (1997), amorphous SiO₂ is not considered a cancer risk, but crystalline silica is.^{13,14} The specific language used in the 1997 and 2012 monographs is included at the end of this section. The Hazard Communication Standard (HCS) requires labeling of materials containing 0.1% or more of a known or potential carcinogen (29 CFR 1910.1200 A.6.3.1).

The risk of silicosis is often considered the well-demonstrated hazard and is regulated explicitly. Indeed, there remains substantial doubt as to whether or not there is a cancer risk in the absence of silicosis.¹⁵ There is also much literature on the high variability of biological response to crystalline silica attributed to such things as the age of crushing.^{4,13} For a discussion of inputs received by the Occupational Health and Safety Administration (OSHA) during the regulatory process, please see Intro to 29 CFR Part 1910, Air Contaminants, Section 6 - VI. Health Effects Discussion and Determination of Final PEL <http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=PREAMBLES&p_id=770>.

Silicosis has been recognized as a specific condition for over a century. The cause has been known for almost 100 years.¹⁶

“Silicosis is a fibrotic lung disease that is caused by overexposure to dusts composed of or containing free crystalline silica. It is irreversible, progressive, incurable, at later stages, disabling, and eventually fatal. The silicosis risk depends on the amount of free crystalline silica inhaled and actually deposited in the alveolar region (hence on the air concentration of respirable dust and its content of free crystalline silica, as well as on the exposure time and breathing pattern). ... Silicosis, like most pneumoconioses, is a chronic disease, taking many years to appear.” page 2, WHO/SDE/OEH/99.14.

Regulations concerning exposure to either amorphous or crystalline silica are therefore especially attentive to material that can get into the alveoli of the human lung. Particles that can consistently do this are commonly termed ‘respirable dust.’ CFR 1910.94(a)(1)(x) states it thus, “Airborne dust in sizes capable of passing through the upper respiratory system to reach the lower lung passages.” Particles unlikely to reach the alveoli are also of concern, and are referred to based on where they typically can reach when inhaled.

*“The American Conference of Governmental Industrial Hygienists (ACGIH), the International Organization for Standardization (ISO), and the European Standards Organization (CEN) have reached agreement on definitions of the **inhalable, thoracic and respirable** fractions. ...*

***Inhalable particulate fraction** is that fraction of a dust cloud that can be breathed into the nose or mouth. ...*

***Thoracic particulate fraction** is that fraction that can penetrate the head airways and enter the airways of the lung. ...*

***Respirable particulate fraction** is that fraction of inhaled airborne particles that can penetrate beyond the terminal bronchioles into the gas-exchange region of the lungs.”* page 8, WHO/SDE/OEH/99.14.

Where a particle can reach is related to the aerodynamic particle size. Aerodynamic size is defined as “the diameter of a hypothetical sphere of density 1 g/cm³ having the same terminal settling velocity in calm air as the particle in question, regardless of its geometric size, shape, and true density,” page 1, WHO/SDE/OEH/99.14.

*“The largest inhaled particles, with aerodynamic diameter greater than about 30 μm , are deposited in the airways of the head . . . Of the particles which fail to deposit in the head, the larger ones will deposit in the tracheobronchial airway region and may later be eliminated by mucociliary clearance (see below) or - if soluble - may enter the body by dissolution. The smaller particles may penetrate to the alveolar region, the region where inhaled gases can be absorbed by the blood. In aerodynamic diameter terms, only about 1% of 10- μm particles gets as far as the alveolar region, so 10 μm is usually considered the practical upper size limit for penetration to this region. Maximum deposition in the alveolar region occurs for particles of approximately 2 μm aerodynamic diameter. Most particles larger than this have deposited further up the lung. For smaller particles, most deposition mechanisms become less efficient, so deposition is less for particles smaller than 2 μm until it is only about 10-15% at about 0.5 μm .
pages 4–5, WHO/SDE/OEH/99.14.*

It is technically possible to measure the abundance and composition of particles in these size ranges but the accuracies are not high, especially as concentrations of crystalline silica phases drop below 1% to 3% (NIOSH, p 264).¹⁸ The details of sampling protocols and the instrumentation become very important; e.g., see Page and Volkwein¹⁹ for a discussion of a technique used in coal mines. A discussion of some technologies used for this purpose may be found in Chapter 8: Sampling Dust in the Work Environment, in Dust Control Handbook for Minerals Processing, February, 1987, Report from Contract No. J0235005 by Martin Marietta Laboratories, 1450 South Rolling Road, Baltimore, MD 21227–3898 <http://www.osha.gov/dsg/topics/silicacrystalline/dust/chapter_8.html>.²⁰

The IARC 1997¹³ monograph states on page 3, “The evaluations for both crystalline and amorphous silica pertain to inhalation resulting from workplace exposures. Lung cancer was the primary focus.” As noted on page 2 of WHO/SDE/OEH/99.14, “In aerosol science, it is generally accepted that particles with aerodynamic diameter >50 μm do not usually remain airborne very long: they have a terminal velocity >7cm/sec. Such large particles neither stay in the air nor pass through the head very easily. Further, in the Preambles to Final Rules for 29 CFR Part 1910, Air Contaminants the “Primary Basis for Limits” is stated to be “respiratory effects.” (Section 2 - II. Index to Preamble Discussion of Individual Substances <http://www.osha.gov/pls/oshaweb/owa-disp.show_document?p_table=PREAMBLES&p_id=766>. And CFR 1910.1200.A.0.2.5, “The effect of a chemical on biological systems is influenced by the physico-chemical properties of the substance and/or ingredients of the mixture and the way in which ingredient substances are biologically available. A chemical need not be classified when it can be shown by conclusive experimental data from scientifically validated test methods that the chemical is not biologically available.” Thus, as a practical matter, if material less than 100 μm can be avoided, it seems there is relatively little hazard to respiratory health.

In the United States the specific regulations pertaining to both crystalline and amorphous silica are given in CFR 1910.1000 TABLE Z-3 Mineral Dusts <http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9994>. These values are for general industries. Specific and more stringent values can apply in specific cases not of relevance here. According to 1910.1000(c), “An employee’s exposure to any substance listed in Table Z-3, in any

8-hour work shift of a 40-hour work week, shall not exceed the 8-hour time weighted average limit given for that substance in the table.” The table provides two ways of quantifying the limit: (1) Millions of particles per cubic foot of air and (2) mg/m^3 . There are values for both respirable and total dust. For example, the permissible exposure limit for respirable quartz is stated as $((10 \text{ mg}/\text{m}^3)/(\% \text{SiO}_2 + 2))$. For total dust, the formula is $((20 \text{ mg}/\text{m}^3)/(\% \text{SiO}_2 + 2))$. The values for cristobalite are one-half those for quartz.

Equipment and standards for making measurements of airborne dust are described in OSHA Technical Manual (OTM) Section II: Chapter 1 PERSONAL SAMPLING FOR AIR CONTAMINANTS, VI. [Respirable Dust](http://www.osha.gov/dts/osta/otm/otm_ii/otm_ii_1.html) and VII [Crystalline Silica](http://www.osha.gov/dts/osta/otm/otm_ii/otm_ii_1.html) <http://www.osha.gov/dts/osta/otm/otm_ii/otm_ii_1.html>. There is also a NIOSH standard procedure manual, NIOSH Manual of Analytical Methods [NMAM], Fourth Edition, March 15, 2003 <<http://www.cdc.gov/niosh/docs/2003-154/>>. This deals with airborne dust only. It is important to note that analysis of bulk samples is different.

9.1 International Agency for Research on Cancer (2012) 5. Evaluation

- There is *sufficient evidence* in humans for the carcinogenicity of crystalline silica in the form of quartz or cristobalite. Crystalline silica in the form of quartz or cristobalite dust causes cancer of the lung.
- There is *sufficient evidence* in experimental animals for the carcinogenicity of quartz dust.
- There is *limited evidence* in experimental animals for the carcinogenicity of tridymite dust and cristobalite dust.
- Crystalline silica in the form of quartz or cristobalite dust is *carcinogenic to humans* (group 1).

9.2 International Agency for Research on Cancer (1997) 5.5 Evaluation

- There is sufficient evidence in humans for the carcinogenicity of inhaled crystalline silica in the form of quartz or cristobalite from occupational sources.
- There is inadequate evidence in humans for the carcinogenicity of amorphous silica.
- There is sufficient evidence in experimental animals for the carcinogenicity of quartz and cristobalite.
- There is limited evidence in experimental animals for the carcinogenicity of tridymite.
- There is inadequate evidence in experimental animals for the carcinogenicity of uncalcined diatomaceous earth.
- There is inadequate evidence in experimental animals for the carcinogenicity of synthetic amorphous silica.

9.3 Overall Evaluation

In making the overall evaluation, the Working Group noted that carcinogenicity in humans was not detected in all industrial circumstances studied. Carcinogenicity may be dependent on inherent characteristics of the crystalline silica or on external factors affecting its biological activity or distribution of its polymorphs.

Crystalline silica inhaled in the form of quartz or cristobalite from occupational sources is carcinogenic to humans (group 1).

Amorphous silica is not classifiable as to its carcinogenicity to humans (group 3).

9.4 Synonyms for Crystalline Silica (IARC 1997)

Following are synonyms for crystalline silica:

Agate	DQ 12	Porosil	Silica W
Chalcedony	Flint	α -Quartz	Snowit
Chert	Jasper	α,β Quartz	Stishovite
Clathrasil	Keatite	Quartzite	Sykron F300
Coesite	Min-U-Sil	Sandstone	Sykron F600
α,β Cristobalite	Moganite	Sil-Co-Sil	$\alpha, \beta 1, \beta 2$ Tridymite
CSQZ	Novaculite	Silica sand	Zeosil

9.5 Synonyms for Amorphous Silica (IARC 1997)

Following are synonyms for amorphous silica:

Aerosil	Diatomaceous earth	Nalcoag	Sipernat
Art Sorb	(uncalcined)	Neosyl	Skamol
Baykisol	Diatomite	Nipsil	Snowtex
Bindzil	Fina/Optima	Nyacol	Spherosil
Biogenic silica	FK	Opal	Suprasil
Britesorb	Fused silica	Precipitated silica	Sylobloc
Cab-O-Sil	Gasil	Quartz glass	Syloid
Celatom	HDK	Reolosil	Sylopute
Celite	Hi-Sil	Seahostar	Syton
Clarcel	Hispacil	Sident	TAFQ
Colloidal silica	KC-Trockenperlen	Silcron	Tixosil
Decalite	Ketjensil	Silica fibres	Tripolite
Diamantgel	Kieselguhr	(biogenic)	Trisyl
Diatomaceous earth	Lucilite	Silica-Perlen	Ultrasil
(flux-calcined)	Ludox	Silica-Pulver	

APPENDIX

The following individuals were notably helpful in the work reported here:

Geological Survey and Regulatory Contacts:

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[Richard B. Moore](#), [Edward W. Wolfe](#), [George E. Ulrich](#), Volcanic Rocks of the Eastern and Northern Parts of the San Francisco Volcanic Field, Arizona, *Journal of Research of the U.S. Geological Survey*, Vol. 4, No. 5, pp. 549–560, 1976.

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Dr. Orris is a specialist in industrial minerals, including basalt quarries.

Academic Contacts

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Michael.Ort@nau.edu

<<http://nau.edu/CEFNS/NatSci/SESES/Faculty/Ort/>>

Dr. Ort is knowledgeable about the volcanics of northern Arizona and some of the surrounding areas.

Chris Condit
U of Mass at Amherst
Dept.: 413–545–2286
Direct: 413–545–0272
Cell: 413–687–1321

ccondit@geo.umass.edu

<<http://www.geo.umass.edu/faculty/condit/>>

<<http://www.geo.umass.edu/people/christopher-d-condit>>

Chris Condit is an expert in the geology of the Springerville Volcanic Field.

Andres Aslan
Dept. Chair, Geology
Colorado Mesa University
Grand Junction, CO
Phone: 970–248–1614

aaslan@coloradomesa.edu

Dr. Aslan kindly collected and sent several volcanic bombs and cinder from this deposit. Photographs of two bombs are used in this Technical Memorandum.

REFERENCES

1. Oravec, H.A.: “Understanding Mechanical Behavior of Lunar Soils for the Study of Vehicle Mobility,” *Interaction Studies*, Case Western Reserve University, Cleveland, OH, 2009.
2. Taylor, P.T.; Lowman, Jr., P.D.; and Chen, P.C.: “GSC-1: A Lunar Simulant from a Jurassic Sill in Leesburg, Virginia,” GSA Northeastern Section (45th Annual) and Southeastern Section (59th Annual) Joint Meeting, March 13–16, 2010: Baltimore, MD: *Geological Society of America, Abstracts with Programs*, Vol. 42, No. 1, p. 53, 2010.
3. Rahmatian, L.A.; and Metzger, P.T.: “Soil Test Apparatus for Lunar Surfaces,” *Earth and Space 2010*, pp. 239–253, doi: 10.1061/41096(366)25, 2010.
4. Schoonen, M.A.A.; Cohn, C.A.; Roemer, E.; et al.: “Mineral-Induced Formation of Reactive Oxygen Species,” in *Medical Mineralogy and Geochemistry: Reviews in Mineralogy and Geochemistry*, Mineralogical Society of America, N. Sahai and M.A.A. Schoonen (eds.), Vol. 64, pp. 179–222, 2006.
5. Heiken, G.H.; Vaniman, D.T.; and French, B.M.: *Lunar Sourcebook: A User’s Guide to the Moon*, Cambridge University Press, 1991.
6. Le Maitre, R.W.: *Igneous Rocks: a Classification and Glossary of Terms, Recommendations of the International Union of Geological Sciences, Subcommission on the Systematics of Igneous Rocks*, 2nd ed., Cambridge University Press, 2002.
7. Rickman, D.L.; Stoesser, D.B.; Benzel, W.M.; et al.: “Notes on Lithology, Mineralogy, and Production for Lunar Simulants,” NASA/TM—2011–216454, p. 64, January 2011.
8. Stoesser, D.B.; Rickman, D.L.; and Wilson, S.A.: “Preliminary Geological Findings on the BP-1 Simulant,” NASA/TM—2010–21644, p. 24, September 2010.
9. Lonsdale, J.T.: *Igneous Rocks of the Balcones Fault Region of Texas*, University of Texas Bulletin 2744, 174 pp., 1927.
10. Zhu, J.: “Petrogenesis of Late Cenozoic Volcanic Rocks from the Raton-Clayton Volcanic Field: Northeastern New Mexico and Southeastern Colorado,” Rice University, Houston, TX, 229 pp., June 1995.
11. Larson, E.E.; Ozima, M.; and Bradley, W.C.: “Late Cenozoic basic volcanism in northwestern Colorado and the origin of the Colorado River system,” B.F. Curtis (ed.), *Cenozoic history of the Southern Rocky Mountains*; Geological Society of America, Boulder, CO, pp. 155–178, 1975.

12. Branch of Industrial Minerals Staff, *Crystalline Silica Primer*. U.S. Bureau of Mines Special Publication, 25 pp. <<http://minerals.usgs.gov/minerals/pubs/commodity/silica/780292.pdf>>, 1992.
13. Silica: Summary of Data Reported and Evaluation, IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Vol. 68, World Health Organization, International Agency for Research on Cancer, 1997.
14. *Arsenic, Metals, Fibres, and Dusts*, IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Vol. 100C, World Health Organization, International Agency for Research on Cancer, 2012.
15. Pelucchi, C.; Pira E.; Piolatto G.; et al.: “Occupational Silica Exposure and Lung Cancer Risk: a Review of Epidemiological Studies 1996-2005.” *Annals of Oncology: Official Journal of the European Society for Medical Oncology/ESMO* 17 (7), pp. 1039–1050, doi:10.1093/annonc/mdj125, July 2006.
16. Russell, A.E.; Britten, R.H.; Thompson, L.R.; and Bloomfield, J.J.: “The health of workers in the the dusty trades, II, Exposure to siliceous dust (granite industry),” Public Health Bulletin No. 187. US Public Health Service, Washington, DC, 1929.
17. World Health Organization, *Hazard Prevention and Control in the Work Environment: Airborne Dust*, WHO/SDE/OEH/99.14, Geneva, Switzerland, 246 pp., <http://www.who.int/entity/occupational_health/publications/en/oehairbornedust.pdf>, 1999.
18. NIOSH Manual of Analytical Methods [NMAM], 4th ed., <<http://www.cdc.gov/niosh/docs/2003-154/>>, March 15, 2003,
19. Page, S.J.; and Volkwein, J.C.: “A Revised Conversion Factor Relating Respirable Dust Concentrations Measured by 10 Mm Dorr-Oliver Nylon Cyclones Operated at 1.7 and 2.0 L Min(-1),” *Journal of Environmental Monitoring*, Vol. 11, No. 3, pp. 684–689, doi:10.1039/b817922k, March 2009.
20. Key-Schwartz, R.J.; Baron, P.A.; Bartley, D.L.; et al.: “Determination of Airborne Crystalline Silica,” *NIOSH Manual of Analytical Methods*, National Institute for Occupational Safety and Health, pp. 260–280, <<http://www.cdc.gov/niosh/docs/2003-154/pdfs/chapter-r.pdf>>, 2003.
21. Carrier III, W.D.: *The four things you need to know about the Geotechnical Properties of Lunar Soil*, Lunar Geotechnical Institute, Lakeland, FL, <http://www.lpi.usra.edu/lunar/surface/carrier_lunar_soils.pdf>, September 2005.
22. Miggins, D.P.; Blome, C.D.; and Smith, D.V.: “Preliminary⁴⁰ Ar/³⁹ Ar geochronology of igneous intrusions from Uvalde County, Texas: Defining a more precise eruption history for the southern Balcones Volcanic Province,” U.S. Geological Survey Open-File Report 2004-1031, 33 pp., 2004.

23. Tran, C.L.; Miller, B.G.; and Soutar, C.A.: *Risk Estimates for Silicosis: Comparison of Animal and Human Studies*, Institute of Occupational Medicine, Research Report TM/05/02, Edinburgh, Scotland, 2005.

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14. ABSTRACT Marshall Space Flight Center (MSFC) has built the Lunar Surface Testbed using 200 tons of volcanic cinder and ash from the same source used for the simulant series JSC-1. This Technical Memorandum examines the alternatives examined for transportation and source. The cost of low-cost lunar simulant is driven by the cost of transportation, which is controlled by distance and, to a lesser extent, quantity. Metabasalts in the eastern United States were evaluated due to their proximity to MSFC. Volcanic cinder deposits in New Mexico, Colorado, and Arizona were recognized as preferred sources. In addition to having fewer green, secondary minerals, they contain vesicular glass, both of which are desirable. Transportation costs were more than 90% of the total procurement costs for the simulant material.					
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